

Fig. 4.1.3 Yearly average atmospheric CO₂ concentrations (1959-2024) measured at Mauna Loa, HI (green) compared to the estimated pre-Industrial CO₂ concentration of 280 ppm, and the estimated minimum levels required to sustain life on Earth (150 to 200 ppm). Need source

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The annual increase in concentration is only about half of the CO₂ emitted because land and ocean processes absorb “excess” CO₂ at a rate approximately 50% of human emissions. Thus, future concentrations, and hence future human influences on the climate, depend upon two components: (1) future rates of global human CO₂ emissions, and (2) how fast the land and ocean remove extra CO₂ from the atmosphere. We discuss each of these in turn.

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4.2 ~~The carbon cycle and~~ Future emission scenarios ~~and the carbon cycle~~

4.2.1 Emission scenarios

Assessing the future dangers of GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic progress, regulation, and the energy and agricultural technologies in use. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Because of the great uncertainties about these many factors in the the decades to come, instead of making precise predictions of future concentrations, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, technology, and so on. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m² of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m².)

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Although the IPCC does not put its emission scenarios forward as forecasts they are often treated as such. Comparisons of past scenario groups against observations shows a tendency for IPCC emission projections to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* were used, and used and hence were referred to as the SREP scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita terms, the SREP scenario distribution was skewed upwards and incompatible with

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observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO₂ emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis in Hausfather *et al.* (2019) who showed that observed atmospheric CO₂ concentrations tracked the low end of the SRES range.

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For the Fifth Assessment Report the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCP). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying a gain-radiative forcing in 2100 of 2.6 W/m²Watts-per-square meter) projects a GHG concentration pathway which leading to implies warming remains well below 2°C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5°C warming just in this century.

RCP8.5 came to be referred to as the no-policy baseline, or "business-as-usual" scenario in both the academic literature and popular media. RCP8.5 came to be referred to as the no-policy baseline, or "business-as-usual" scenario. It was therefore used in this way to generate the reference outcome supposedly representing the 21st century world in the absence of emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its usage as a business-as-usual baseline has been criticized as grossly misleading.¹ Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as an extreme worst-case, and its misuse as a "business as usual" baseline has resulted in a large number of misleading studies and media reporting:

RCP8.5 was intended to explore an unlikely high-risk future. But it has been widely used by some experts, policymakers and the media as something else entirely, as a likely 'business as usual' outcome. A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy-modelling literature.

(Hausfather and Peters 2020)

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed energy use trends, and the near future trends diverge sharply from those of the International Energy Agency (IEA) which provides market-based projections of energy use for coming decades. IEA trends are

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¹ This extreme scenario is useful for modelers, since a large forcing generates a large response (warming), making it easier to assess a model's sensitivity. But that's very different than claiming it is a plausible future.

based on plausible extrapolations of current economic and demographic trends, and the results run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but even lower emission scenarios are looking unlikely. Burgess *et al.* comment (p. 8):

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Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil-fuel expansion in these scenarios that are increasingly implausible.

Widespread use of RCP8.5 has ~~created an alarmist caused a bias in the climate impacts literature towards alarmism in the climate impacts literature.~~ The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found (p. 32) that ~~some 16,800 scientific papers published between 2010 and 2020 some 16,800 scientific papers had been published using~~ the RCP8.5 scenario, ~~and (p. 16) that with about 4,500 of the articles (p. 16) linked~~ RCP8.5 with the concept of “business-as-usual”. Their ~~analysis sy-provided analyses of howed~~ how RCP8.5 was misused not only by individual researchers, but ~~also~~ by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets. They ~~provide-offer~~ the following example (p. 30):

The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic estimates of the benefits of mitigation. In a front-page story, the *New York Times* promoted the report’s misuse of RCP8.5 as a baseline scenario:

“A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century’s end.”

Pielke and Ritchie (2020) reported new studies using RCP8.5 were appearing in the literature at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude (p. 34) that the climate research community has spent a decade “committing scientific resources to science fiction” (emphasis added):

“Derived estimates from RCP8.5 as “business as usual” such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and

benefits of mitigation have no real-world meaning... **The scientific literature has become imbalanced in an apocalyptic direction.**

(Pielke Jr. and Ritchie p. 34)

The IPCC later converted the RCP scenarios to the "Shared Socioeconomic Pathway" or SSP scenarios, but these have continued the pattern of bias shown with the RCP and SRES scenarios. Figure 3.14 was generated using the Resources for the Future Global Energy Outlook tool (RFF 2025). The black line shows total global observed CO₂ emissions from compiled by the International Energy Agency (IEA). The solid green line is the emission trajectory developed by BP Energy taking account of current emission control policies and global energy use outlooks. It overlaps a solid black line which represents the emission projection from the IEA also taking account of energy use projections and current policies. The dashed lines show the range of IPCC SSP policies. As of 2023 global CO₂ emissions have been tracking well below the SSP scenarios especially the two highest ones (SSP5-8.5 and SSP3-7.0).

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Carbon dioxide emissions (Million metric tons), by Outlooks & Scenarios. Filtered by Region: World; Fuel: All; Outlook: 2023 Shell (Sky 2050).

Source: RFF Global Energy Outlook at www.rff.org/geo

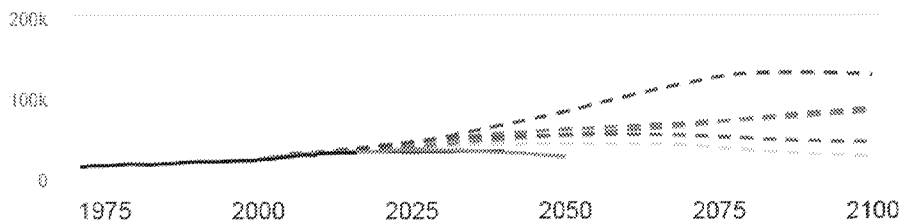


Figure 4.2.1. Observed and projected CO₂ emissions. Source: RFF (2025).

4.2.2 The carbon cycle relating emissions and concentrations

Global carbon cycle models relate concentrations to emissions using estimates of various land and ocean processes that remove CO₂ from, and emit CO₂ into, the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021).

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The natural fluxes of CO₂ in and out of the Earth's surface are very large, many times anthropogenic emissions, but those CO₂ sources and sinks were assumed to be in approximate balance in pre-Industrial times, as evidenced by relatively constant levels of atmospheric CO₂ in centuries past derived from air bubbles in ice cores. This is one of several reasons why increasing atmospheric CO₂ levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO₂ levels in the atmosphere, as shown in Fig. 1.2.1. CO₂ emissions from fossil fuel burning is a small fraction of the natural carbon cycle components. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO₂. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al. 2024). Of this, about half is naturally sequestered through plant growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

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As noted, each year natural processes remove a net amount of CO₂ equivalent to about 50% of global emissions. Thus, anthropogenic CO₂ emissions average twice what is required to explain the atmospheric rise in CO₂ concentration. The near-constancy of that 50% fraction (the "airborne fraction") also means that the more CO₂ humanity produces, the faster Nature removes it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Niño, La Niña, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO₂ after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes which remove excess CO₂ from the atmosphere are increased production of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO₂ by the ocean due to the increasing partial pressure of atmospheric CO₂ over that of CO₂ dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO₂ at an increasing rate since 1959. This is consistent with a "global greening" phenomenon observed by satellites since monitoring of global greenness began in the 1982. This greening has been traced to CO₂ fertilization and greater drought tolerance of plants exposed to elevated CO₂ levels. While there had been some uncertainty whether a greening trend continued beyond 2000, the

most recent research (Chen et al., 2023) has shown continued greening, with even some slight acceleration since 2000. Global greening is discussed further in Section 3.1.

While land vegetation has been responding positively to more atmospheric CO₂, uptake of extra CO₂ by ocean biological processes remains too uncertain to be reliably measured. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp et al. (2021).

Public policy can only change the rate of emissions, not the concentration in the atmosphere. For criteria air contaminants the rate and concentration are closely connected because the lifetime is short and the concentration is small. When emissions are reduced the local pollution concentration drops rapidly, usually on a time scale of a few days. Not so with the global average CO₂ concentration since global carbon cycle is vast and slow. A change in local emissions today will only have a very small global effect, and only after a long time lag. After a pulse (release) of CO₂ emissions to the atmosphere only about 40 percent ($\pm 15\%$) of the extra CO₂ will have been sequestered after twenty years. After a thousand years about 75 percent ($\pm 10\%$) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently US CO₂ emission reductions will take decades or centuries to lead to a reduction in the global CO₂ concentration.

To reduce the atmospheric stock of CO₂, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. Since that rate has been averaging about 50% of emissions, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO₂. The 1997 Kyoto Protocol proposed to cap industrial nations' CO₂ emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy ended up being too costly for most nations to implement, full compliance would not have substantially reduced atmospheric CO₂ levels. It would only have slightly slowed CO₂ growth, reaching the projected 2100 level in 2105 instead (Wigley 1998). Similarly, Lomborg (2016) used the widely-used MAGICC climate model and showed that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, local actions yield extremely small local effects, and only after a long time lag. The practice of referring to unilateral US reductions as "combating climate change" or "taking action on climate" reflects a profound misunderstanding of the scale of the issue. The scale problem is compounded by recognizing that US motor vehicles account only for about 4 percent of global CO₂ emissions so even a fifty percent reduction in those emissions would have a vanishingly small effect on the global climate.

4.3 Aerosols and the uncertainties associated with them

The role of this chapter should be to address radiative forcing – not ECS or warming attribution. I think that the material in this section should be moved to ECS or attribution. There is huge uncertainty in the aerosol indirect effect, which relates directly to radiative forcing. I can write up something on this

~~THIS PARA SHOULD BE DELETED HERE. THIS IS COVERED IN THE ATTRIBUTION CHAPTER. The climate's sensitivity to CO₂ (as quantified by ECS, the Equilibrium Climate Sensitivity²) is uncertain (Equilibrium Climate Sensitivity or ECS) cannot be directly measured in part because the anthropogenic radiative forcing is uncertain because the net forcing because results from it represents the net effect of (at least) two counteracting force components: warming from GHGs and cooling from aerosols. The observed warming can therefore be made to be consistent with a wide range of pairs of these forces. In the following schematic, the net warming represented by the red arrow could be due to the High GHG warming/strong aerosol cooling pair, or the Low GHG warming/weak aerosol cooling pair, or something in between.~~

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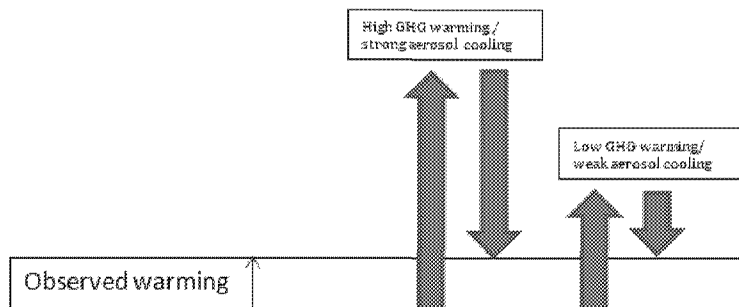


Figure 4.3.1: High and low climate sensitivity to GHGs can be reconciled with the same warming by assuming an offsetting aerosol cooling effect.

² ECS is formally defined as the increase in equilibrium global average surface temperature resulting from a doubling of the atmospheric CO₂ concentration above its pre-industrial value of 280 ppm. Estimates of ECS are reviewed in Section XX.

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~~THIS CAN GO IN ECS CHAPTER~~ Consequently, ~~research~~ Research on the strength of aerosol cooling is ~~hereby~~ central to ~~forming~~ ~~valid~~ more precise ECS estimates. Lewis and Curry (2018) note that after the IPCC AR5 was published in 2013, eleven studies appeared in the scientific literature all finding that aerosol cooling was weaker than had previously been conjectured. Combining the updated aerosol estimates with greenhouse gas, ocean heat uptake and atmospheric warming data from the IPCC and applying standard empirical methods, Lewis and Curry (2018) estimated the best-guess ECS to be 1.66°C with a 95 percent uncertainty range of 1.15 °C – 2.7°C. They concluded that based on the ECS values derived from most IPCC climate models were incompatible with observed data.

~~There has been further evidence of lower aerosol cooling (implying lower ECS) has continued to be found, such as Liu et al. (2021).~~ ~~THIS COULD BE MADE TO BE RELEVANT TO RADIATIVE FORCING CHAPTER~~ ~~Liu and his co-authors~~ These authors tested the hypothesis that aerosols from wildfires has increased since before the 20th century which, if true, would mean there had to have been relatively strong CO₂ warming over that period offsetting the aerosol cooling. They examined soot layers in ice cores extracted from Antarctica and South America and determined that wildfire activity prior to the 20th century was higher than previously believed. Instead of wildfire activity rising steadily from the 1700s to the present, it was high all the way along time, ~~thus which means there was no increase in aerosols over that time—therefore the contradicting the previously hypothesized aerosol cooling trend in the Southern Hemisphere over during the 20th century did not happen.~~ They pointed out how this finding relates to the climate sensitivity issue:

Accurate estimates of aerosol radiative forcing are also crucial for better understanding the transient climate response (TCR) and equilibrium climate sensitivity (ECS) to increasing CO₂ and more accurate projection of future climate change. The negative aerosol radiative forcing can, in part, cancel out the positive forcing of increasing greenhouse gases and contribute to the uncertainty of total radiative forcing. An overly large aerosol cooling implies that models might overestimate TCR and ECS to reproduce historical temperature response. A recent study using one of the latest-generation CMIP6 climate models (E3SM) suggested that reducing both the magnitudes of negative aerosol radiative forcing and climate sensitivity yields a better agreement with the observed historical record of the surface temperature.

(Liu et al. 2021)

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Liu told the UK Daily Mail³

~~Climate scientists have known that the most recent generation of climate models have been over-estimating surface temperature sensitivity to greenhouse gases, but we haven't known why or by how much. This research offers a possible explanation.~~

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I really think we should limit direct quotes to IPCC or other official docs, or something that is especially profound.

More evidence pointing to weak aerosol cooling was reported by Wang *et al.* (2021). They noted that the strength of aerosol cooling is partly mediated by cloud behavior and differs between the North and South Hemispheres because of the different density of aerosol emissions. This allowed them to construct another test of climate model validity, which came out in favor of low ECS models. In their words:

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Since anthropogenic aerosols primarily concentrate in the Northern Hemisphere, strong aerosol-cloud interaction models produce an interhemispheric asymmetric warming. We show that the observed warming asymmetry during the mid to late 20th century is more consistent with low ECS (weak aerosol indirect effect) models. PARAPHRASE, DIRECT QUOTE NOT NEEDED

Wang et al. (2021)

THIS PARA IS AN ATTRIBUTION STATEMENT, NOT A FORCING STATEMENT To summarize, measuring the effect of quantifying warming due to CO₂/CO₂ warming requires making an assumption about understanding the strength of aerosol cooling. While that later it is very uncertain a substantial body of recent evidence points to it being relatively weak, which implies that CO₂ warming is likewise weak. The literature estimating ECS will be reviewed in Section XX.

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Summary

- The global climate is naturally variable. Anthropogenic CO₂/CO₂ emissions add to that variability by changing the total radiative balance in the atmosphere.
- The IPCC has downplayed the potential role of the sun in climate change but there are Total Solar Irradiance reconstructions that imply it may/might have played an important role/been important, and the modern record is uncertain due to an interruption in satellite coverage.

³ Available online at [HYPERLINK "<https://www.dailymail.co.uk/sciencetech/article-9629919/Climate-change-warming-effect-greenhouse-gases-overestimated-ice-core-study-suggests.html>"]

- When Projections of anthropogenic emissions are combined estimates along with carbon cycle model estimates of atmospheric CO₂ removal are combined we get estimates of future CO₂ concentrations and hence the radiative forcings. These are input to required by climate models to estimate future anthropogenic changes in the climate rates of warming.
- IPCC emission scenarios envelopes have tended to exceed observed trends.
- The vast majority of academic climate "impacts" studies in recent years are based upon the extreme RCP8.5 scenario that is considered implausible, and its usage as a business-as-usual scenario is misleading.
- Despite ample evidence that scenario envelopes are exaggerated, and despite criticism of this practice in the peer-reviewed literature, the IPCC's most recent scenario set called (SSP) carries on with perpetuates this pattern of practice.
- The global carbon cycle heavily dampens the effect of changes in local (e.g. U.S.) CO₂ emissions. Even global-scale emission reductions will have only small, much delayed effects, long in the future.
- ~~Measuring Knowing the effect magnitude of CO₂ warming requires making an assumption about knowing the strength of aerosol cooling. While that is very uncertain, a substantial body of recent evidence points to it being relatively weak, which implies implying CO₂ warming is likewise weak. THIS IS AN ATTRIBUTION STATEMENT.~~

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10. Climate change and US agriculture

10.1 Evidence based Econometric analyses on land values

Scientists have long known about the beneficial effect of CO₂ on plant growth and have studied it extensively. Thousands of experiments in laboratories and outdoor field settings (CO2Science.org, undated) have confirmed beneficial effects for food plants and crops of all kinds from higher CO₂ levels.

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should translate into higher market values for agricultural land, and vice versa. While individual crops might benefit from or be harmed by climate change, once the adaptive responses of farmers are taken into account the value of farmland represents an index of whether the changes are expected to be beneficial or not. Evidence that CO₂-induced warming will be neutral or beneficial for agriculture, particularly in the US, goes back decades. Mendelsohn et al. (1994) examined the effects—relationship between of historical climatic variations on agricultural land values and concluded “our projections suggest that global warming may would be slightly beneficial to American agriculture.” Mendelsohn et al. (2000) provided a global assessment of the impacts of 2°C warming by 2060, (which would be equivalent to 3.3 °C warming per century). They concluded that 2°C warming “will result in net market benefits for most OECD countries”. Tol (2003) published estimates of the global impact on agriculture of a 2.5 degree C warming. Assuming farmers adapt to the changes, he expected every region to end up better off.

The Mendelsohn et al. method, called Ricardian analysis after David Ricardo, the 19th century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached similar conclusions to Mendelsohn et al. (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the US agricultural sector. However a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in US agriculture due to climate warming. Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

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DESIGNING LAND VALUE ARE YOU JUST TALKING ABOUT AGRICULTURE OR SOMETHING ELSE? Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by

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taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100. There have been criticisms of the methodology used by Mendelsohn et al. (1994) to associate land value changes with climate change. It was later criticized by others for potentially leaving out other important determinants of land value that change over time, such as what, leading some authors to argue that the benefits of warming would be much smaller or even negative. Bareille and Chakir (2023) addressed the criticisms by assembling a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. By comparing the change in land value on the same farm to local climatic and economic changes they were able to remove the confounding influence of fixed site-specific characteristics and isolate the contribution of climate variables. They concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, climate changes anticipated under the medium RCP4.5 scenario could add 100% to double the value of French farmland by 2100. They also noted that application of earlier methods to the same data would suggest climate change would be harmful to French agriculture.

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A major deficiency of all these studies, however, is that they omit the role of CO₂ fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO₂. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO₂ that drives them. As explained in Chapter 2, CO₂ is a major driver of plant growth so this omission biases the analysis towards underestimation of the benefits of climate change on agriculture.

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10.2 Field studies of CO₂ enrichment

As discussed in Chapter 2, I PREFER TO SEE THIS MATERIAL IN CHAPTER 10 RATHER THAN IN CHAPTER 2. Scientists have used so-called Free Air CO₂ Enrichment, or FACE, experiments to measure how well plants in outdoor settings responds in outdoor settings to local increases in the level concentration of carbon dioxide. One of the ways the effect of CO₂ on crop growth has been studied is through "free air enrichment experiment" or FACE plots, in which small chimneys are placed in fields surrounding plants and the growth response to elevated CO₂ under varying weather conditions are recorded. Ainsworth et al. (2020) summarizes results from about 250 such studies. They found that elevation of CO₂ by 200 ppm cause an average 18% increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions. In For instance in a 2021 study that reviewed 160 FACE experiments conducted over 20 years, Hu et al. (2021) concluded that elevated CO₂ levels had boosted rice growth on average by 16 percent. Furthermore, when they looked at hybrid varieties especially particularly suited to the higher CO₂ levels, the growth increased by was nearly 25 percent.

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In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO₂ on all kinds of plant growth. Here we review some of the results on key US agricultural crops.

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Soybean

Studies on the impact of elevated CO₂ on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO₂ concentrations resulted in improved photosynthesis rate, water use efficiency and growth (Li, 2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. In addition there were 10 studies reporting on +600 ppm CO₂ enrichment, resulting in an average increase in photosynthesis of 90.3%.

Maize (corn)

The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO₂. An experimental study (Allen Jr, 2011) exposed plants to water stress conditions in sunlight controlled environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO₂. The drought stress caused a 41% loss of growth under ambient CO₂ but only a 13% loss under elevated CO₂.

Wheat

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured the yield as well as nutritional quality of an "improver" hybrid wheat variety and its parents under elevated CO₂ levels (+166 ppm). They reported a grain yield increase of +16% but a 7% decrease in grain protein levels. But they found that the food quality of different wheat varieties responded differently to elevated CO₂ levels, so that with proper varietal selection end-users can select wheat types that best take advantage of the elevated CO₂.

Further evidence

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Wheat also benefits from CO₂-induced climate change. The website CO2Science.org {[HYPERLINK "http://www.co2science.org/data/plant_growth/photo/t/triticuma.php"](http://www.co2science.org/data/plant_growth/photo/t/triticuma.php)} reports on 92 published experiments between 1983 and 2020 exposing wheat to enriched CO₂ levels. Converted to a +300 parts-per-million common scale, the average growth boost was 67.6 percent.

A 2021 report from the US National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO₂ levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that since 1940 CO₂ emissions had boosted US cropproduction since 1940 -by 50 to 80 percent, attributing much larger attributable gains than had previously been estimated using FACE experiments. They found that every 1 part per million ppm of increase in CO₂ levels concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.

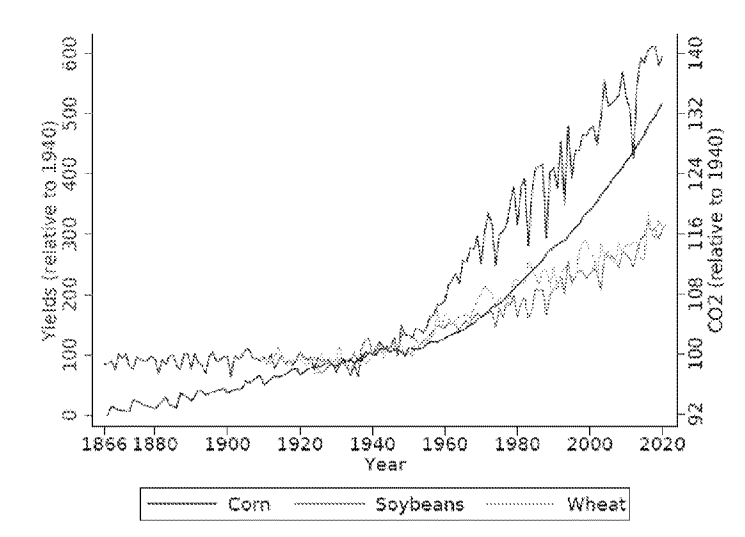


Figure 10.1: US average CO₂ levels and yields of corn, soy and wheat all normalized so 1940=100.
Source: Taylor and Schlenker (2021)

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In addition to Beyond growth benefits, extra CO₂ boosts plant resilience to heat. Derying et al. (2016) surveyed all available evidence regarding how wheat, maize, rice and soybean will grow under a combination of climate warming and rising CO₂ levels. Duplicative of Ch 2, I prefer this material in Ch 10 They concluded that warming would, eventually, have a negative effect on plant growth but it would be fully compensated for by the extra CO₂ for wheat and soybean, and almost completely fully for rice and maize. Also And as discussed in Chapter 2, the plants use water more efficiently when become far more efficient in their water usage when there is more CO₂ in the air.

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Derying et al. (2016) surveyed evidence on crop water productivity (CWP), i.e. yield per unit of water used, drawing attention to the potential for CO₂ both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO₂ fertilization predicted CWP losses but CO₂ fertilization more than offset them and once it was taken into account all regions showed a net CWP gain. Derying et al (2016) also reported that negative impacts on wheat and soybean yields were fully offset by CWP gains, and mitigated by up to 90% for rice and 60% for maize.

Similar to this, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO₂ uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryn et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO₂ levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”. Increased desertification will happen in at most 4% of currently arid areas.

Adaption plays a key role in exploiting gains from climate change for US crops. Butler et al. (2016) examined US maize production since 1981 and found that weather changes had been a net benefit. They also found that “current farmer cropping schedules are more beneficial in the climate of the last decade than they would have been in earlier decades” and adaptive responses to warming had added 13 kg per hectare to maize production. They estimated that weather trends since 1981 had raised boosted US maize production by 28% since 1981.

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10.3 Crop modeling meta-analyses

Notwithstanding the abundant evidence of for the direct benefits of CO₂ and of CO₂-induced warming on crop growth, in 2023 the US Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based in large part on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore et al. 2017) which had come to very pessimistic conclusions. One of the two damage models used by the EPA (Moore et al. 2017) attributed nearly half of the 2030 SCC to projected global agricultural damages based on a The Moore et al. (2017) analysis. Challinor data base was This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. 2017 Moore et al. projected declining global crop yields for all crop types in all regions due to warming.

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McKittrick (2025) re-examined the C14 Challinor Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries (N=862) had complete records, so that. Thus, the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the variable most commonly missing was the change in ambient CO₂ and. He found that in many cases these could be recovered from the underlying studies or the original climate scenario tables. He and thereby increased the usable sample size by 40 percent. After incorporating the newly available data. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 10.12, whereas the partial data set implied warming would cause decrease yield declines (blue lines), the complete data set implied constant or increase global yields, would remain constant or increase globally even out to 5°C warming (green lines).

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In summary, there is abundant evidence going back decades that rising CO₂ levels benefit plants including agricultural crops, and that CO₂-induced warming will be a net benefit to US agriculture. The warming since 1981, in combination with adaptive behaviour by farmers, has been beneficial on its own for maize. The increased ambient CO₂ has also boosted productivity of all major US crop types. Various attempts to argue that CO₂-induced warming will harm agriculture have not held do not hold up under scrutiny.

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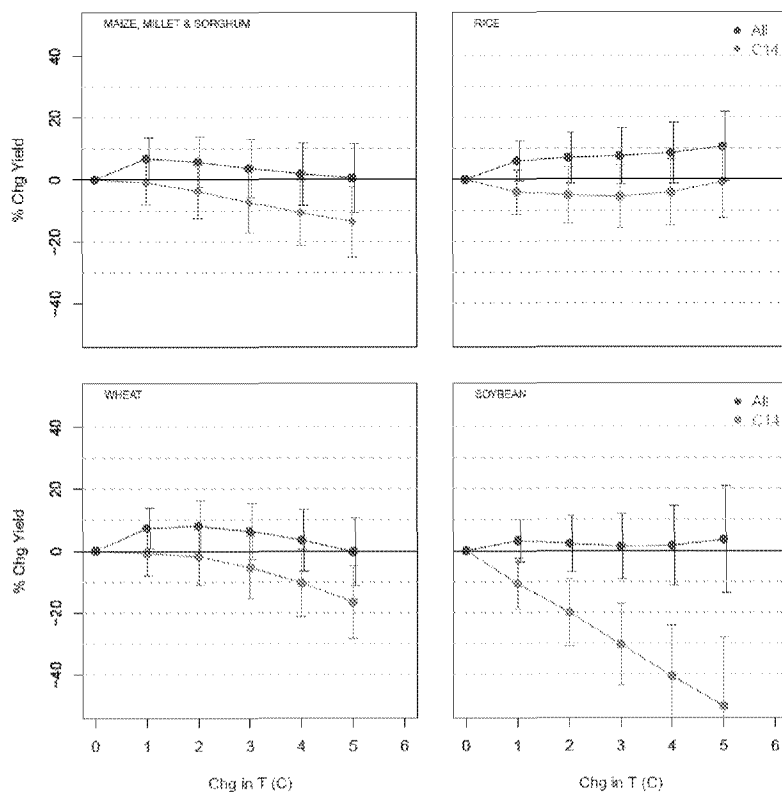


Figure 10.3-2 Crop yields under CO₂-induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).

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Deschênes, Olivier and Michael Greenstone (2007) The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather *American Economic Review* Feb 2007, Vol. 97, No. 1, Pages 354-385

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Deschênes, Olivier and Michael Greenstone (2012) The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather: Reply to Comment
American Economic Review, 102, no. 7: 3761-3773. [HYPERLINK
"http://hdl.handle.net/1721.1/82641"]

Ortiz-Bobea, Ariel (2019) The role of nonfarm influences in ricardian estimates of climate change impacts on US agriculture, American Journal of Agricultural Economics, 102 (3), 934–959.

Schlenker, Wolfram and Michael Roberts (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change, Proceedings of the National Academy of Sciences 106 (37) 15594-15598 [HYPERLINK "https://doi.org/10.1073/pnas.0906865106"]

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10. Climate change and US agriculture

10.1 Ricardian analysis

Scientists have long known about the beneficial effect of CO₂ on plant growth and have studied it extensively. Thousands of experiments in laboratories and outdoor field settings (CO2Science.org, undated) have confirmed beneficial effects for food plants and crops of all kinds from higher CO₂ levels.

Evidence that CO₂-induced warming will be neutral or beneficial for agriculture, particularly in the US, goes back decades. Mendelsohn et al. (1994) examined the effects of historical climatic variations on agricultural land values and concluded "our projections suggest that global warming may be slightly beneficial to American agriculture." Mendelsohn et al. (2000) provided a global assessment of the impacts of 2°C warming by 2060, (which would be equivalent to 3.3 °C warming per century). They concluded that 2°C warming "will result in net market benefits for most OECD countries". Tol (2002) published estimates of the global impact on agriculture of a 2.5 degree C warming. Assuming farmers adapt to the changes, he expected every region to end up better off.

There have been criticisms of the methodology used by Mendelsohn et al. (1994) to associate land value changes with climate change. It was later criticized by others for potentially leaving out other important determinants of land value that change over time, such as what, leading some authors to argue that the benefits of warming would be much smaller or even negative. Bareille and Chakir (2023) addressed the criticisms by assembling a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. By comparing the change in land value on the same farm to local climatic and economic changes they were able to remove the confounding influence of fixed site-specific characteristics and isolate the contribution of climate variables. Those authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, climate changes anticipated under the medium RCP4.5 scenario could add 100% to double the value of French farmland by 2100. They also noted that application of earlier methods to the same data would suggest climate change would be harmful to French agriculture.

THE PREVIOUS PARAGRAPHS ARE CONFUSING. I WOULD JUST TALK ABOUT AGRICULTURE AND NOT LAND VALUE UNLESS YOU DEFINE NON-AG VALUES

10.2 Field studies

As discussed in Chapter 2, scientists have used so-called Free Air CO₂ Enrichment, or FACE, experiments to measure how well plants in outdoor settings responds in outdoor settings to local increases in the level-concentration of carbon dioxide. In For instance in a 2021 study that reviewed 160 FACE experiments conducted over 20 years, Hu et al. (2021) concluded that elevated CO₂ levels had boosted rice growth on average by 16 percent. Furthermore, when they looked at hybrid varieties especially particularly suited to the higher CO₂ levels, the growth increased by was nearly 25 percent.

Wheat also benefits from CO₂-induced climate change. The website CO2Science.org ([HYPERLINK "http://www.co2science.org/data/plant_growth/photo/t/triticuma.php"]) reports on 92 published experiments between 1983 and 2020 exposing wheat to enriched CO₂ levels. Converted to a +300 parts per million common scale, the average growth boost was 67.6 percent.

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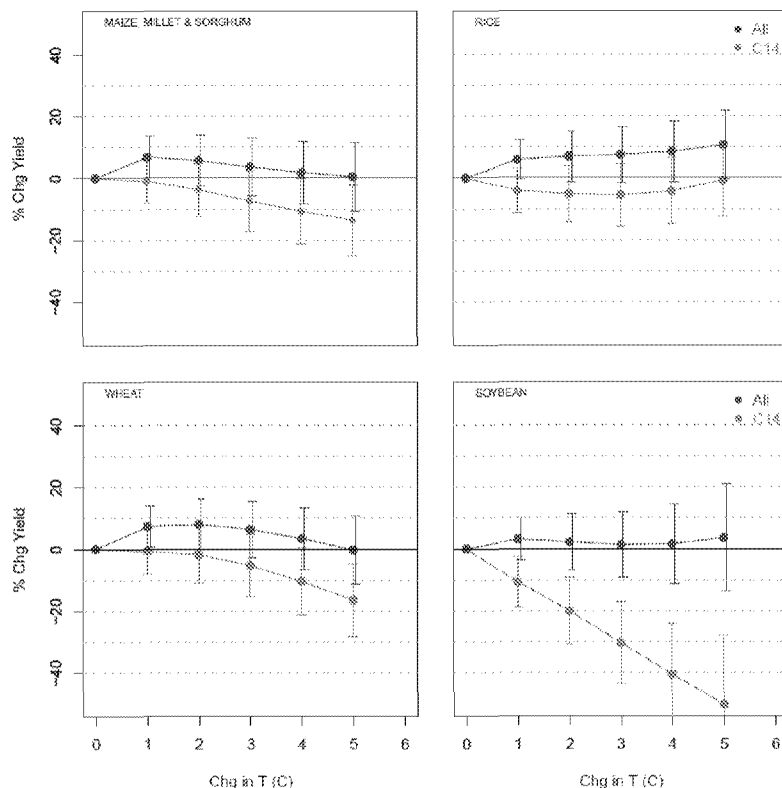


Figure 10.1 Crop yields under CO₂-induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).

Critique of the Fifth National Climate Assessment

[TOC \o "1-3" \h \z \u]

EXECUTIVE SUMMARY

This report critically evaluates the Fifth National Climate Assessment (NCA5), finding it an inadequate basis for climate and energy policies. A detailed review of the foundational chapters on climate science raises several key concerns:

Scientific Integrity

- An advocacy tone, particularly in the Overview chapter, that is inconsistent with scientific objectivity
- Endemic overconfidence when stating conclusions, including inflated certainty levels and overstatement of findings from underlying sources

Flawed methodology

- Use of short time periods for trend analyses; more generally lack of a consistent rule for choosing time scales
- Overemphasis on extreme scenarios for future emissions and sea level rise
- Inadequate traceable accounts to support key conclusions

Deficient Review Process

- A review by the National Academy of Sciences, Engineering, and Medicine (NASEM) failed to challenge some fundamental flaws in NCA5
- The NCA5 authors failed to adopt some improvements recommended by NASEM

The report shows NCA5 to be a biased and incomplete picture of climate science that skews toward excessive climate risk. Consequently, NCA5 should not be used as basis for climate and energy policies.

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1 INTRODUCTION

1.1 About this Report

This report responds to a request from the Office of Science and Technology Policy (OSTP) Director Michael Kratsios (reproduced in Appendix 1) that we assess the suitability of the Fifth National Climate Assessment (NCA5 2023) for informing climate and energy policies.

To conduct this assessment, we reviewed NCA5 itself, the National Academies of Science, Engineering and Medicine (NASEM) review of the Third Order NCA5 Draft, and the USGCRP responses to that review. We have drawn upon our long experience working on advisory reports, including for the NASEM, the Intergovernmental Panel on Climate Change (IPCC) and other organizations, as writers, reviewers and study leaders.

We find that NCA5 should not be relied on for policy making as it is an incomplete and misleading picture of our understanding of the changing climate and the risks it poses to the nation. NCA5 was selective and incomplete in its survey of climate science. Further, we have reviewed recent scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025, herein denoted “CWG25”). The overall effect of the biases and omissions of NCA5 is an excessively dire picture of climate risk.

To support our finding, the following sections of this chapter provide some background on the National Climate Assessments and the standards by which we have assessed NCA5. Chapters 2 through 7 detail important ways in which NCA5 fails to meet those standards. Finally, Chapter 8 summarizes our evaluation of NCA5 and makes recommendations for NCA6.

1.2 About the National Climate Assessments

The [[HYPERLINK "https://www.globalchange.gov/"](https://www.globalchange.gov/)] (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate “a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change.”

The National Climate Assessment (NCA) Reports evolved from the GCRA requirement to:

Prepare and submit to the President and the Congress an assessment which (1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

The five NCA Reports to date have interpreted this mandate in different ways:

- NCA1 (2000) was a multidisciplinary effort to study and portray in regional detail the potential effects of human-induced global warming on the United States.

- NCA2 (2009) was a relatively short report that not only focused on the potential consequences of climate change but also sought to identify potential adaptation measures and identify the highest priorities for future research.
- NCA3 (2014) was an expanded effort that continued along the lines of NCA2, and was distinguished by a comprehensive review process, including a review by the National Academy of Sciences. NCA3 introduced a traceability analysis for each key finding, including a description of uncertainties.
- NCA4 (2017/2018) was a further expanded effort that was published in two volumes: I Climate Science Special Report (CSSR), and II Impacts, Risk, and Adaptation in the United States. This was the first NCA report to devote significant effort to assessing climate science.
- NCA5 (2023) returned to a single volume format, reducing discussion of climate science to a cursory two chapters, with continuing focus on regional and sectoral impacts of climate change. NCA5 expanded its remit to topics that are arguably outside the purview of the USGCRP, focusing on “Climate Action” and policy recommendations with a social justice emphasis.

These successive interpretations of the NCA are poorly aligned with the GCRA’s statutory requirements. Only NCA4 gives serious consideration to climate science, which receives the great majority of USGCRP funding, and even then NCA4 misrepresents some important points. Natural climate variability is essentially dismissed as unimportant in NCA4 and barely mentioned in NCA5 in most contexts, despite the mandate to include both human-caused and natural climate change. Most significantly, NCA5 has redirected the focus away from climate science and even the hazard elements of impacts, towards evaluation of societal vulnerabilities and advocacy for particular policy options, especially deployment of wind and solar generation. The cover image for the NCA5 Report is the installation of a solar panel.

1.3 Standards for Assessing NCA Products

Beyond the statutory requirements stated above, another pertinent standard is President Trump’s executive order of May 23, 2025, [[HYPERLINK "https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/"](https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/)]. It enumerates some of the characteristics of good science, namely that it should be:

- i. reproducible;
- ii. transparent;
- iii. communicative of error and uncertainty;
- iv. collaborative and interdisciplinary;
- v. skeptical of its findings and assumptions;
- vi. structured for falsifiability of hypotheses;
- vii. subject to unbiased peer review;
- viii. accepting of negative results as positive outcomes; and
- ix. without conflicts of interest.

Although these should be self-evident to those trained in science, it is surprising that some scientists have found them controversial (Dellawalla et al. 2025).

====debated text:

When science is assessed for the purpose of climate policymaking there are further requirements to bear in mind. Good climate and energy policies should balance the risks and benefits of a changing climate against the world's growing demand for reliable and affordable energy. To strike that balance, policymakers must understand at least two complex and nuanced topics: the certainties and uncertainties of climate science and the technoeconomic realities of energy systems. Experts in those subjects have a responsibility to communicate their understanding to non-experts clearly, completely, and without bias.

Much expertise in energy systems resides in the private sector, where it is essential to providing the reliable and affordable energy services that are the lifeblood of society. Understanding is therefore continually refined and tested by operational demands and the discipline of the marketplace. In contrast, climate science expertise is found largely in the non-profit realm of universities and government laboratories and so has a more academic character, with greater uncertainties and hence need for expert judgement.

=====

For those reasons assessments of climate science that will be influential for policy making must include statements about the strength of knowledge. The IPCC's approach to assessing strength of knowledge is based on judgment of the available evidence and agreement among experts. But there are more sophisticated knowledge characterizations for risk management. Here are the elements according to Aven (2017):

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
- The degree to which data/information exists and are reliable and relevant
- The degree to which there is disagreement among experts (including those from different environments or academic fields)
- The degree to which the phenomena involved are understood and accurate models exist
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns (issues that are known to matter but are ignored, such as, in this context, natural variability).

1.4 When Peer Review Failed

Peer review of reports like IPCC and NCA products is not a silver bullet that guarantees quality. The peer review process for these reports differs in some important respects from traditional peer review in academic journals. First, during the open review phases of early NCA drafts reviewers are volunteers who self-select what parts of the report to read, whereas the editors of academic journals recruit reviewers with relevant expertise and assign them to specific papers. As a result, there is no guarantee at that stage that any particular section of an NCA report was reviewed by anyone, let alone by someone with relevant expertise and a perspective that differs from the authors. In fact, many potential reviewers have given up over the years because their input has been systematically ignored. The introduction of a NASEM review stage is at best a partial remedy for this. However, NCA authors have near complete authority whether to accept or reject reviewer comments. By contrast, the Editor of an academic journal mandates the author to respond, and the reviewer and Editor assess its adequacy. Finally, the work of an NCA chapter author team is guaranteed to be published, whereas academic journals routinely reject papers that do not pass review.

These points are important to bear in mind because some readers might dismiss any criticism of NCA products out of hand on the grounds that they were "peer reviewed". But the test of a report is

whether its contents are a valid representation of the available evidence. Here we give an example in which NCA4 gave prominence to a figure that completely misrepresented the underlying data and which evaded peer review to do so. Further details can be found in Koonin (2024).

NCA4's Part I says (prominently and with *Very High Confidence*) on Page 19 of the Executive Summary:

There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records.

and offers this figure in support:

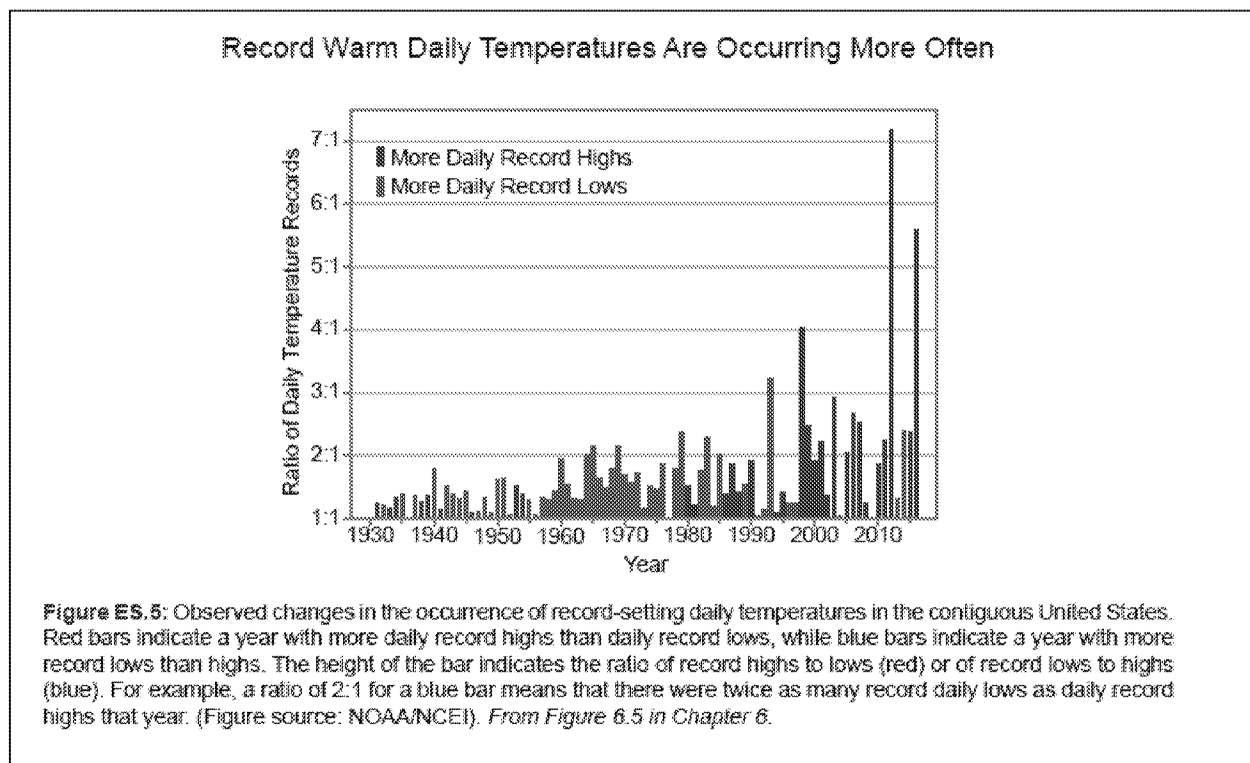


FIGURE 1: Reproduction of Figure ES.5 from NCA4

The figure appears to validate the claim that record warm daily temperatures are occurring more often. But the underlying data do not. Rather, they show that extreme heat in the U.S. peaked in the 1920s and 1930s and declined thereafter, as supported by Figure 6.4 deep within the CSSR itself (reproduced in Section 4.2 of this report).

Figure ES.5 does not even show what its title implies, as it displays not simple counts of cold and warm extreme events, but rather ratios of the two counts. As defined in the analysis, both types of extremes declined over the sample interval, but cold events declined more than warm events, so the ratio of warm extremes to cold extremes increased. By graphing the ratio instead of counts, NCA4 created a visual impression opposite to what is in the data.

Figure 6.3.3 of CWG25 (reproduced below) shows the results of a proper analysis and presentation of the data – defining each record as the singular extreme in the sample interval, displaying numbers of warm and cold records separately, and beginning the analysis in 1899 rather than 1930. It makes evident the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. (The increased heat of the past five years is too brief to be deemed climatically significant and, in any event, occurred after the CSSR was published in 2017.) The frequency of cold records has declined, especially over the last quarter of the period in which only 13 percent of the extreme cold events were measured. In contrast, 25 percent of the heat records were achieved in the last quarter, which is consistent with statistical expectations. As a result, the ratio of hot to cold extremes shown in Figure ES.5 of the CSSR explodes in recent decades. The overall reduction in numbers of both cold and hot extremes over the past century indicates a climate *less* prone to extremes, in sharp contrast to the message of NCA4 Figure ES.5.

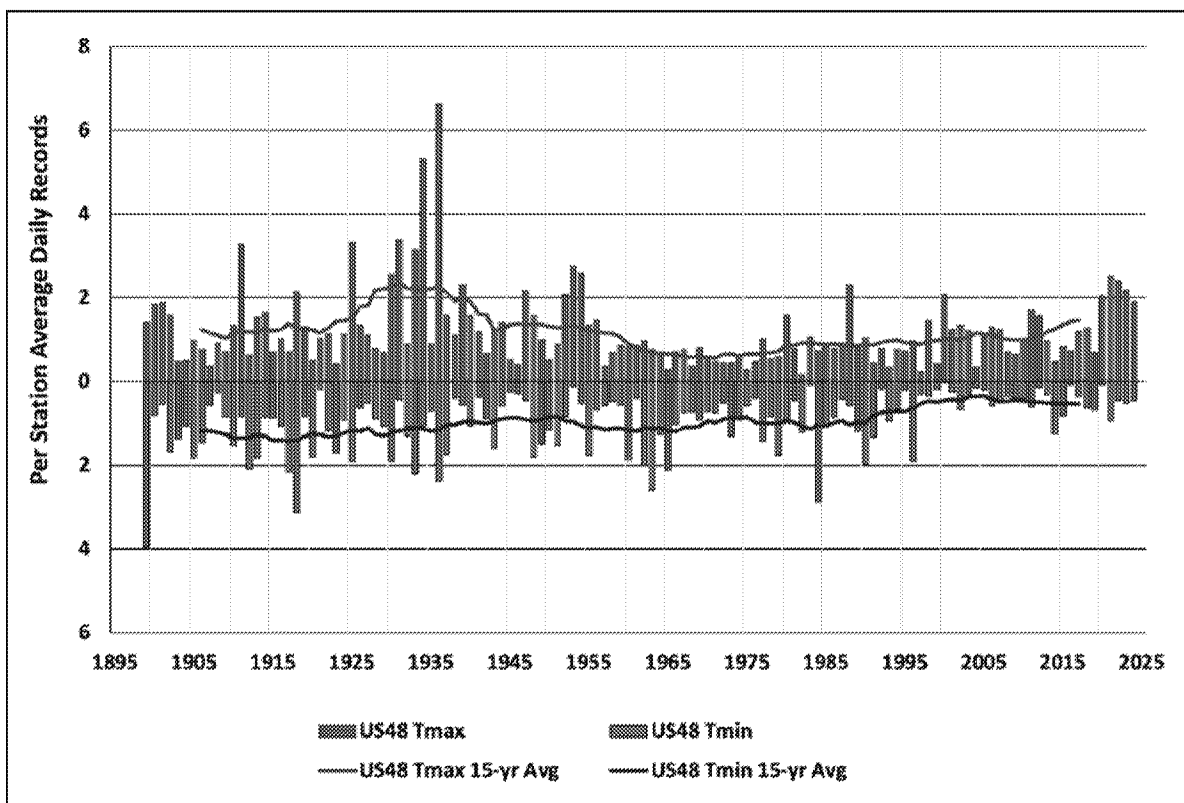


FIGURE 2: Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92 percent of observations in the 126-year period since Dec 1898. US48: contiguous U.S. states. Tmax: maximum temperature. Tmin: minimum temperature. Source: CWG25 Figure 6.3.3.

How did the flawed figure ES.5 pass the NCA4 NASEM Review? The NASEM Review panel [[HYPERLINK "https://www.nap.edu/catalog/24712/review-of-the-draft-climate-science-special-report"](https://www.nap.edu/catalog/24712/review-of-the-draft-climate-science-special-report)] the discussion of temperature extremes in a [[HYPERLINK "https://biotech.law.lsu.edu/blog/Draft-of-the-Climate-Science-Special-Report.pdf"](https://biotech.law.lsu.edu/blog/Draft-of-the-Climate-Science-Special-Report.pdf)]t of the CSSR. Key Finding 2 of Chapter 6 in that draft stated:

Accompanying the rise is [*sic*] average temperatures, there have been – as is to be expected – increases in extreme temperature events in most parts of the United States. Since the early 1900s, the temperature of extremely cold days has increased throughout the contiguous United States, and the temperature of extremely warm days has increased across much of the West. In recent decades, intense cold waves have become less common while intense heat waves have become more common. (*Extremely likely, Very high confidence*)

In reference to this NASEM said:

Further, it is difficult to understand how a statement that includes increases in extreme warmth can be associated with a high confidence or extremely likely statement, given that most of the graphics in this chapter show a decrease in extreme warmth in the historical record.

The Federal official in charge of the CSSR (Michael Kuperberg, Executive Director of the USGCRP) [[HYPERLINK "https://science2017.globalchange.gov/PDFs/CSSR-NASresponse_110217.pdf"](https://science2017.globalchange.gov/PDFs/CSSR-NASresponse_110217.pdf)] to the Academies' review by noting that

Almost every recommendation from the NAS was incorporated [in the final version]... and a new figure was added on changes in record high and low temperatures

The “new figure” referred to is the misleading Figure ES.5, which did not appear in the draft reviewed by the Academies’ panel. It seems unlikely that the Academies panel ever saw that figure because they surely would have commented if they had and it wouldn’t have survived to publication. And the figure’s problems were evidently not flagged (or were ignored) in the subsequent internal government reviews.

With this background from NCA4, we now present our critique of NCA5.

2 NCA5 OVERVIEW CHAPTER: HYPERBOLIC ADVOCACY LANGUAGE AND UNSCIENTIFIC TONE

NCA5 Chapter 1, “Overview”, holds a prominent place in the Report since it summarizes the entire report and is the only section that many will read. Although some material in the later chapters of NCA5 is not without merit, Chapter 1 is marred by an activist tone and language that aggressively promotes mitigation policies. As such, this chapter adds an imprimatur of scientific authority to naïve and simplistic declarations of opinion about public policy. Many examples can be cited; here we note a few that are particularly egregious.

Chapter 1 opens as follows:

The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each

additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases.

This statement presupposes that all warming is anthropogenic, that all warming is bad and causes economic damage, and that warming intensifies extreme weather. Such sweeping generalizations go well beyond what science has or can establish. The statement also refers to growing risks without saying whether they were large to begin with – a small risk that grows may still be a small risk, and a large risk may be only incrementally worsened.

On the next page the Overview states:

Each additional increment of warming leads to greater risks [here it lists 7 key components of society including food security and the economy]... Without deeper cuts in global net emissions, climate risks to the US will continue to grow... Action to limit future warming and reduce risks can have near-term benefits and opportunities: low-carbon energy jobs, Improved air quality, Health benefits, Economic benefits...”

The authors write as if climate policy does not involve trade-offs and all measures to reduce future warming will be effective and beneficial. Neither the vast body of scholarship on climate science and economics, nor historical experience, support such simplistic claims (CWG25 ch.XX). Not every additional increment of warming leads to economic harms; in fact, NCA5 Chapter 19 acknowledges that there will also be benefits. Nor is climate policy guaranteed to benefit the economy; it could impose net costs. Such misleading statements are a disservice to policymakers.

Pages 8 and 9 of the Overview promote renewable energy options by noting, correctly, that the levelized costs of wind/solar generation have fallen sharply since 2010, and so offers this rationale for pursuing deep emission reductions:

Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources.

Yet it has long been known that intermittent renewables generation must be supplemented by dispatchable generation to meet grid reliability standards, and that doing so (e.g., through natural gas, fission, or storage) significantly increases the cost of electricity. Further, there are yet unmet synchronization challenges in electrical grids with heavy penetration of wind and solar generation. Here again it is advisory malpractice not to acknowledge these facts. But more importantly, we see no reason for NCA5 to be discussing renewable energy technologies and economics in the context of its mandate.

Page 14 of the Overview presents future emission scenarios with the following description: “Climate modeling experts develop global climate projections for a range of plausible futures.” The word “plausible” is applied to all the scenarios. The accompanying figure includes both SSP3-7.0 and SSP5-8.5, the latter reaching the same radiative forcing as RCP8.5. The figure does not compare observed emissions with previous projections, nor does it caution readers that SSP3-7.0 and SSP5-8.5 are extreme scenarios that, like RCP8.5, have been heavily criticized in the scientific literature as being implausible (CWG25 3.2.1). By describing the entire envelope of emission projections as “plausible”

the report opens the door to later presenting impacts associated with implausible worst case emission scenarios as part of a baseline “business-as-usual” future.

Page 17 of the Overview introduces the discussion of risks from extreme weather events by saying “Harmful impacts from more frequent and severe extremes are increasing across the country.” This creates the impression that extreme weather events are worsening and that disaster losses are driven by trends in extreme weather. While the section goes on to acknowledge that some of the increase is due to increases in the value of assets at risk, it then invokes the NOAA Billion Dollar Dataset as evidence of extreme weather getting worse. Scientists have shown that this is an invalid metric (CWG 10.2) since it measures the growth of the economy not the frequency of extreme weather, and indeed NOAA has recently withdrawn the data product (Pielke Jr. 2024, 2025). Even though the dataset was still distributed by NOAA at the time of the NCA5, the report authors failed to assess it skeptically and see that it was unfit for the purpose of measuring climate trends.

Page 23 of the Overview states, in large font:

Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities.

It is pointless to try to evaluate this statement on scholarly grounds; it is self-evidently hyperbolic. This kind of language doesn’t belong in a scientific assessment report. Its prominent inclusion points not only to the willingness of NCA5 authors to promote alarm, but also the ineffectiveness of the review process in eliminating such statements.

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS

3.1 Inflated certainty levels

Overconfidence in stating conclusions has been an endemic problem in NCA Reports. The authors frequently make sweeping generalizations without appropriate caveats or acknowledging uncertainties. The overconfidence begins with inflated language to describe certainty levels.

NCA5 uses specific terms to convey information about scientific confidence associated with important finds, observations and projections. The Front Matter of NCA5 states that

confidence in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.

and Table 1 from the Front Matter provides calibrated language for confidence assessment:

Very high:	Strong evidence (established theory, multiple sources, well documented and accepted methods, etc.). High consensus
High:	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.). Medium consensus
Medium:	Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) Competing schools of thought.

Low: Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.). Disagreement or lack of opinions among experts.

This terminology is obviously inflated: *high confidence* with just moderate evidence and medium consensus; *medium confidence* with only suggestive evidence and competing schools of thought. This inflation in terminology leads to overconfidence in conclusions.

Even with this inflated terminology, NCA5 further inflates the confidence level of many of its conclusions to well beyond what the IPCC has concluded with more thorough justification, and by incorrectly applying its own standards. An example is the conclusion about anthropogenic influence on climate change, arguably one of the most important scientific statements of the report.

Key Message 3.1 Traceable Account states:

There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused *all* global warming observed over the industrial era.

while the corresponding statements from IPCC AR5 and AR6 are

AR5: It is *extremely likely* that *more than half* of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. (IPCC, 2013)

AR6: The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.

The IPCC AR5 and AR6 statements provide likelihood assessments but not a confidence level. While NCA5 claims with *very high confidence* that fossil fuels have unequivocally caused *all* global warming, AR5 refers to “*more than half* of the observed warming” and AR6 provides a more nuanced statement that relates to a *likely* range of warming contributed to by human drivers.

3.2 Overstating findings in underlying sources

Although we did not do a detailed audit of NCA5’s use of source material, spot checks suggest a pattern of overstatement.

Chapter 2 page 11 reports on an increase in precipitation in some areas and attributes it to “climate change”:

Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

The claims were attributed to Knutson and Zeng (2018). But Knutson and Zeng did not say these things nor analyze this particular period. They said (emphasis added):

Observed annual precipitation trends over the recent 30-yr period 1981–2010 ([HYPERLINK "https://journals.ametsoc.org/view/journals/clim/31/12/jcli-d-17-0672.1.xml" \l "fig5"]) have generally stronger magnitudes (in mm yr⁻¹ decade⁻¹) than observed trends for 1901–2010 or 1951–2010. This is as expected since trends over a shorter period have stronger potential for occurrence of pronounced temporary trends due to internal variability alone. **Only 9% of the analyzed area has detectable and attributable anthropogenic influence (categories –3, –2, +2, +3), which represents less than one-third of the fractional areal coverage of such trends for 1901–2010 (29%).** ... Eight percent of the analyzed area has attributable anthropogenic *increases* (categories +2, +3), including parts of eastern Europe, northern Asia, northern Australia/Maritime Continent, and tropical Africa.

Thus for 1981–2010 they cautioned that observed changes are consistent with natural variability, and they did not claim attributable trends were observed over the United States.

As another example of overstating findings, NCA5's Chapter 2 page 18 states

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.

This is apparently attributed to two papers Diffenbaugh *et al.* (2018) and Kirchmeier-Young and Zhang (2020). Diffenbaugh *et al.* presented ratios of observed occurrences of extreme events to simulated occurrence rates in CMIP6 models run with only natural forcings. They report that for 79% of the U.S., extreme rainfall events are currently more frequent than in simulations, and the ratio of occurrences will rise under future warming simulations. This is not “robust” evidence of anthropogenic influence since it requires readers to assume that climate models accurately simulate regional precipitation patterns, something that even IPCC AR6 admits is uncertain (AR6 WGI SPM Box SPM 1.2, SPM Section C.1.3).

Kirchmeier-Young and Zhang looked at extreme 1- and 5-day events in North America and, using three global climate models, found

A signal of combined anthropogenic and natural external forcing can be detected in the intensification of extreme precipitation at the continental scale over North America. In some cases, this intensification can be attributed to human influence specifically.

However, they noted large differences among the three models in their simulated precipitation changes, and two of the three models failed to yield attribution for 5-day events for the North America mean. In other words, the models disagreed on whether the observed changes were anthropogenic. Both of the cited references utilized the implausible RCP8.5 scenario and began their “historical” observational records only in 1961. Here again this is not “robust” evidence, it is merely suggestive, particularly since other studies have found natural variability predominant.

3.3 Technical example: Emergent constraints

Some of the overconfidence expressed by NCA5 arises by omitting discussion of counterevidence in the peer reviewed literature. An example is the topic of “emergent constraints”. Chapter 3 page 17 invokes this concept to support its claim that key uncertainties in climate model projections have been reduced:

An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as “emergent constraints.” The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship.

Emergent constraints appeared in the climate modeling literature as an attempt to tie climate model behavior to climate observations in hopes of generating insight into real-world equilibrium climate sensitivity to a doubling of carbon dioxide (ECS). Climate models exhibit a wide range of ECS values. The idea of emergent constraints is to examine whether the models with shared sensitivity values also share a common representation of some climate process (usually related to clouds) that might influence ECS. Suppose, for instance, that in low-ECS models the total cloud fraction in the tropics is strongly correlated with that in the southern midlatitudes, but in high-ECS models the correlation is weak. Then researchers could examine whether the observed correlation is strong or weak and draw a conclusion about which type of model, and therefore which ECS value, is more likely.

A problem in the emergent constraint literature is that there has been a proliferation of proposed correlations with little physical motivation. NCA5 alludes to this in the Traceable Accounts section (p. 3-40) but not in the main Chapter text. As shown by Schlund *et al.* (2020) many emergent constraints patterned on CMIP5 models (Coupled Model Intercomparison Project No. 5, used for the IPCC 5th Assessment Report) failed to work on CMIP6 models (used for the IPCC 6th Assessment Report). In other words, the observed correlations in CMIP5 models between ECS and cloud processes failed to show up in CMIP6 models, indicating that they were likely spurious rather than clues to physical processes governing the climate system. As a result, emergent constraints estimated on CMIP5 models *increased* the uncertainty of ECS, rather than decreasing it as intended and as claimed by NCA5.

Schlund *et al.* summarized the problem as follows [**boldface** added for emphasis]

In this study, we systematically analyze 11 published emergent constraints on ECS that have mostly been derived from models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) project... The focus of the study is on testing if these emergent constraints hold for [Earth System Models] participating in the new Phase 6 (CMIP6). Since none of the emergent constraints considered here have been derived using the CMIP6 ensemble, CMIP6 can be used for cross-checking of the emergent constraints on a new model ensemble. **The application of the emergent constraints to CMIP6 data shows a decrease in skill and statistical significance of the emergent relationship for nearly all constraints, with this decrease being large in many cases.** Consequently, the size of the constrained ECS ranges (66% confidence intervals) widens by 51% on average in CMIP6 compared to CMIP5.

Yet NCA5 described the use of emergent constraint analysis as an advance that reduced uncertainty of ECS and climate model projections (p. 3-38):

Emergent constraints have been widely applied to reduce the simulated spread in the climate feedbacks that shape climate sensitivity.

4 ARBITRARY AND AMBIGUOUS TREND ANALYSIS

In CWG25 Chapter 6 we discussed the need for care in the choice of time scale when making claims about trends in extreme weather. We provided examples from analysis of river flooding, heatwaves, and extreme precipitation to show how assertions about apparent trends based on short data sets fall apart when looking at longer versions of the same data sets. NCA5 uses varying time scales for trend discussions, especially in Chapter 2 (which is focused on trends), without explaining why shorter or longer intervals were chosen. For example, page 2-4 defines temperature trends with respect to the interval since the late 1800s whereas page 3-29 presents temperature trends over 1972-2021. Page 2-11 compares rainfall over the 2002-21 versus 1901-1960 intervals while page 2-18 uses the interval since the late 1950s to compute trends.

A further problem is that NCA5 uses term “trend” repeatedly without indicating if it is statistically significant (*i.e.* distinguishable from random variability); the ambiguity creates the impression all the observed changes were significant, but readers are left to speculate. All climate variables will, in principle, drift up or down over any particular time interval. Identifying the change as a trend requires showing that it is statistically significant using a variance estimator suitable for the type of data being analysed. Of particular importance is choosing a method robust to serial correlation which is frequently present in climate data. Throughout Chapters 1 to 3 references are made to “trends” without explaining how they were computed. The exception was on page 1-19 which refers to urban temperature trends being calculated using the Theil-Sen estimator, although that method does not seem to have been used elsewhere. The one case where reference is made to statistical significance was on Page 2-9 referring to a trend in Atmospheric Optical Depth but no explanation is given of how significance was determined. Page 2-19 refers to regional trends in droughts being “robust” but again fails to explain how the term was defined.

In this chapter when we refer to calculation of trends in precipitation, we use ordinary least squares to compute the linear trend over the entire sample length and we use the Vogelsang and Franses (2007) variance estimator which is robust to general forms of serial correlation.

4.1 Average and Extreme Precipitation

McKittrick and Christy (2019) showed that trends in U.S. average and extreme precipitation that appeared to be positive and significant over the NCA4 interval (1901 – 2016) lost significance and/or changed sign on longer samples (extending back as far as the 1840s, depending on location) or on a shorter interval coinciding with the final 40 years of the data then available (1978 – 2017). In CWG25 Section 6.4 we presented analyses of updated data for the same locations (and many others), in all cases finding both considerable regional heterogeneity and that trends detectable on one time scale are often not detected on longer or shorter time scales. These findings argue against simple attribution of changes to anthropogenic influences.

NCA5 did not continue the NCA4 precedent of using the post-1901 interval as the time scale for its precipitation discussion. Instead it refers to changes “since the 1950s”; NCA5 Figure 2.8 suggests 1958 might be the intended start date. Under Key Message 2.2 “Extreme Events Are Becoming More Frequent and Severe” (p. 2-16) NCA5 states (p. 2-18):

Rainfall is becoming more extreme

Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US. This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity.

In addition to our concerns that inferences about trends are contingent on choice of time scale, if the intended meaning of this statement is that positive and significant trends are found in heavy precipitation events across CONUS we cannot reproduce it. We supplemented the data used in CWG25 (McKittrick and Christy 2025a) with 61 stations across the Midwest (Christy 2025). Many post-1950 trends are positive but statistically insignificant depending on the measure of extreme precipitation. It is possible to find locations that positive and significant trends, such as the Southeast post-1950, but those results are not robust to selecting longer or shorter time scales of analysis nor do they generalize across all regions (see details in McKittrick and Christy 2025b).

The following is a more accurate summary of what U.S. precipitation data show.

There are regionally heterogeneous changes in average and extreme precipitation. Positive trends in annual average rainfall and extreme events (defined either as the annual maximum or the number of exceedances of the 99th percentile value) are generally weak or non-existent when looking at samples exceeding 130 years in length. Significant trends can be found when beginning the sample in the 1950s although in most cases the trends weaken and become insignificant when looking at the post-1980 interval. This argues against attribution of changes in precipitation to anthropogenic warming.

4.2 Heatwaves

In contrast to NCA5, NCA4 examined heat extremes across the entire 20th century, pointing out that peak heat wave activity was reached in the 1930s and has decreased since then, and that recent increases are confined to areas west of the Rockies. NCA4 stated:

[The] warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]).

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

(NCA4 pp. 190-191)

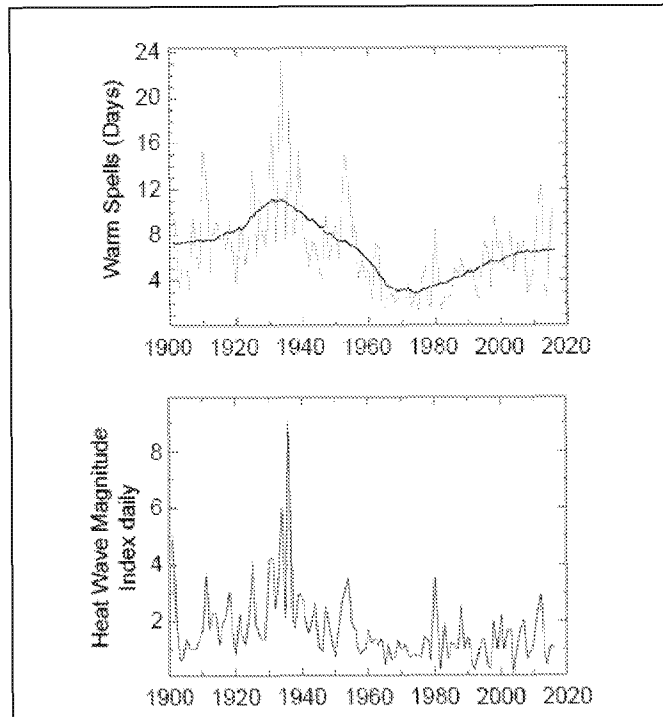


FIGURE 3. U.S. Heat waves since 1900. Reproduction of NCA4 Figure 6.4

Contrast this careful and factual language from NCA4 with NCA5 Key Message 2.2: “Extreme Events Are Becoming More Frequent and Severe.” This blanket statement is followed by NCA5 Figure 2.7 (reproduced as Figure 4 below) which shows the number of hot days, cold days and warm nights (respectively in panels a—c) over the period 2002-2021 compared to 1901-1960. [Presumably these are annual counts, although not stated in the caption.]

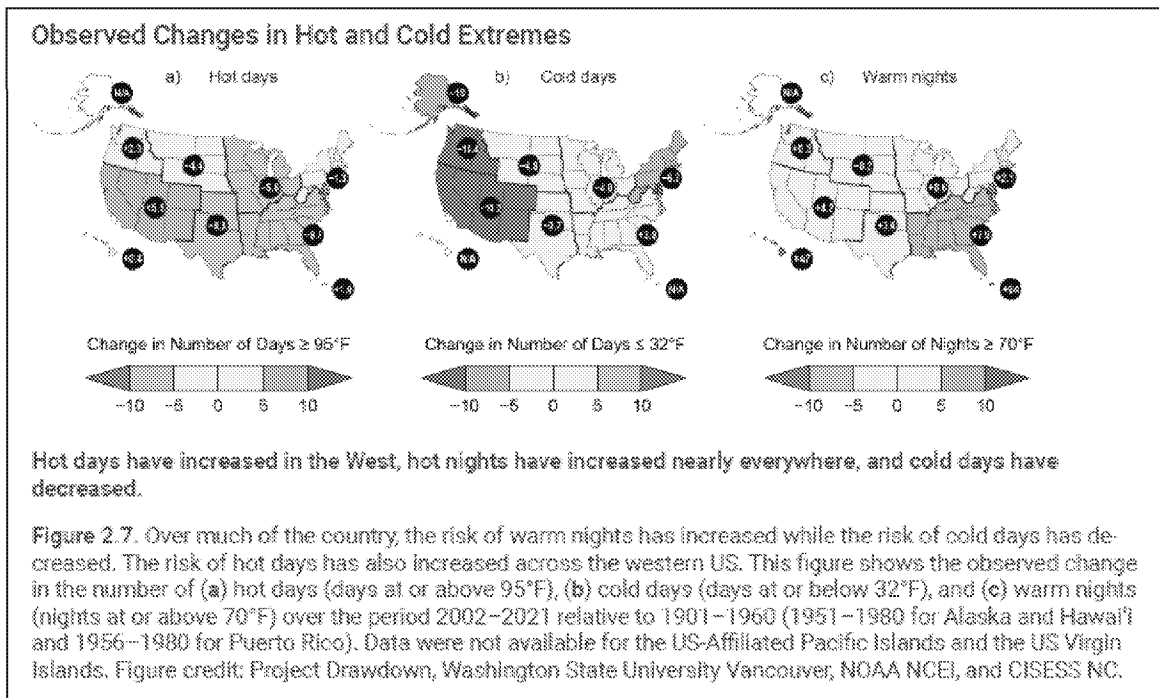


FIGURE 4: Reproduction of NCA5 Figure 2.7.

Close inspection shows that this figure actually contradicts the NCA5 Key Message with respect to heatwaves and instead reinforces the position of NCA4. Notwithstanding Key Message 2.2, the leftmost panel in NCA5 Figure 2.7 above shows that over most of CONUS the number of extreme heat days has *decreased* in recent decades compared to the prior century.

The accompanying discussion in NCA5 becomes convoluted as it appears to be aimed at supporting the Key Message despite the contrary evidence. NCA5 Chapter 2 elaborates on Key Message 2.2 by stating (page 16):

Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*).

But while it mentions the increase in hot days in the West, it fails to mention the decrease everywhere east of the Rockies. On the next page (page 17) it raises the comparison to the 1930s and then switches to discussing global counts:

By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s. ... Globally such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends.

The reference to a global trend seems to be an attempt to tie heatwaves to anthropogenic climate change. But the obvious question, unaddressed by NCA5, is why one region follows the global pattern of increasing heatwaves while most of the country is trending in the opposite direction. These issues are addressed in Chapter 6 of CWG25, demonstrating that the range and magnitude of extreme temperatures (10s of degrees) are driven more by natural variability than by the small anthropogenic forcing. The analysis in CWG25 shows that for both (a) hot days ($\geq 95^{\circ}\text{F}$) and (b) number of days in heatwaves, the current decade is no hotter than a century ago in the U.S. Thus, the NCA5 claim that

“multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades,” is simply false when expanding the temporal and spatial domains to encompass all available data (Chapter 6 and Figure 6.3.6 of CWG25).

NCA5 then pointed to the dramatic Pacific Northwest heatwave of 2021. CWG2025 Section 8.6.1 discussed this event in detail, reviewing the multiple peer reviewed studies that explained the unusual meteorological context was unrelated to human-caused climate change, a point omitted from the NCA5 discussion.

NCA5 finally addresses the declining heatwave trend in CONUS east of the Rockies but attempts to reframe it by focusing on urban warm spells.

[The] number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades. Across 50 large US cities, the US Global Change Research Program heatwave indicator ([[HYPERLINK "https://www" \].globalchange.gov/indicators/heat-waves](https://www.globalchange.gov/indicators/heat-waves)) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.

We discussed this part of NCA5 in CWG25 Section 6.3. The figure referenced by NCA5 uses a short time period which begins in the 1960s, the coldest decade in the last 100 years, thus suppressing any comparison to the 1930s. Further, nighttime temperatures in urban areas have increased faster than daytime temperatures (which NCA5 acknowledges), but this is a signature of urban heat islands and not a good metric of climate change. CWG25 found that the occurrence of hot days ($\geq 95^{\circ}$ F) has recently increased in the West, but declined in the remainder of the country, and in the nationwide average, since 1899.

5 INADEQUATE TRACEABLE ACCOUNTS

NCA3 began the practice of including a section on Traceable Accounts at the end of each chapter. This is the description from NCA5:

Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team’s expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

The Traceable Accounts for each Key Message includes the following sections:

- Description of Evidence Base

- Major Uncertainties and Research Gaps
- Description of Confidence and Likelihood

The Traceable Accounts could have addressed the statutory requirement that the NCA discuss scientific uncertainties. They could also help satisfy the Executive Order for Restoring Gold Standard Science by addressing reproducibility, transparency, communication of error and uncertainty, and skepticism of findings and assumptions. However, the Traceable Accounts in NCA5's Chapters 2 and 3 are uneven, often superficial and uninformative.

An example of a deficient Traceable Account is NCA5's Key Message 2.2: "Extreme Events are Becoming More Frequent and Severe". The "Description of the Evidence Base" offers two paragraphs, the first summarizing the findings and the second generically describing the types of data that can be used for storms. "Major Uncertainties and Research Gaps" focuses on the uneven distribution across U.S. populations due to differences in exposure and vulnerability. The only limitations in data referred to are the lack of a long-term record of lightning and the lack of homogenized daily and hourly temperature data apart from reanalysis products.

But the most astonishing deficiency is in the "Description of Confidence and Likelihood." One of the statements in Key Message 2.2 is:

Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*).

The Description of Confidence and Likelihood includes the following statement:

Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have high confidence that storms are delivering more rainfall and high confidence that storm surges are becoming higher.

No reference to journal publications or a specific data set is made anywhere in the chapter regarding hurricane-induced precipitation or storm surge to support this *high confidence* conclusion.

The Traceable Accounts for the various Key Findings of Chapter 3 have some substantial inconsistencies. Consider

Key Message 3-1: Human activities have caused global warming.
Confidence and Likelihood: "There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have *unequivocally* caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over this period."

The Uncertainties section addresses only uncertainties in radiative forcing by greenhouse gases, ignoring the great uncertainty in model response (CWG25 Chapters 4&5) In contrast, the Traceability Analysis of Key Message 3-4 ("Humans Are Changing Earth System Processes") raises the problem that relatively little is known about the role of natural variability at the regional scale. From its Description of Evidence Base:

In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals.

And from its Major Uncertainties and Research Gaps:

For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

These statements are among the most scientifically credible in the entire NCA5 and they directly undercut the confidence assigned to Key Message 3-1.

There is also a generic problem in tracing NCA5's Traceable Accounts. The Front Matter of NCA5 states:

Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation.

Clicking on the 'eyeball' icon does not reveal the metadata information; instead a "Contact Us" email appears, addressed to the USGCRP. This is an inadequate way to archive the metadata information.

In summary, the Traceable Analyses examined here, with few exceptions, fail to meet the stated objectives of the NCA.

6 OVEREMPHASIS ON EXTREME SCENARIOS

To respond to the GCRA mandate to "project major trends for the subsequent 25 to 100 years," NCA5 relies on projections of future climate change based on estimates of future emissions (the so-called SSP scenarios) and/or specified levels of radiative forcing (the RCP scenarios). For the most part, NCA5 uses scenarios developed for the IPCC Assessment Reports.

In CWG Section 3.2.1 we presented a critical assessment of past and current IPCC scenario envelopes, showing that they have tended to overshoot observed emissions. IPCC AR6 published in 2021 stated that "The likelihood of high-emission scenarios like RCP8.5 and SSP5-8.5 is considered low in light of recent energy sector developments." and that same year UN Climate Negotiators (COP) stopped using scenarios above 4.5.

NCA5 makes the following observations about the scenarios they use:

NCA5 authors were advised to assess the full range of scenarios available. (Front Matter)

Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that

the highest scenario, SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency. (Key Message 3.3 Traceable Analysis)

Despite acknowledging the issue, NCA5 otherwise ignored the problem. A keyword search of NCA5 of mentions of RCP/SSP scenarios finds over 50% referred to the extreme emissions scenarios RCP8.5/SSP5-8.5. Further, nine NCA5 figures (5.2, 6.9, 7.4, 11.3, 14.6, 22.13, 22.19, 27.9, 29.13) included *only* the 8.5 scenarios.

The problem of relying on extreme scenarios is particularly acute for NCA5's sea level rise projections. The sea level rise scenarios used in NCA5 do not relate directly to the SSP emissions scenarios, but rather to specified amounts of sea level rise by 2100. Table 4 of NCA5's "Guide to Using this Report" reproduced below shows that Low relates to 0.3 m (0.98 feet), Intermediate-Low relates to 0.5 m (1.64 feet), Intermediate relates to 1.0 m (3.28 feet), Intermediate-High relates to 1.5 m (4.92 feet), and High relates to 2.0 m (6.56 feet).

Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5						
Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2022. ¹¹						
Sea Level Rise Scenario Descriptor	Global Mean Sea Level			United States		
Year	2050	2100	2150	2050	2100	2150
Low	0.49 (0.15)	0.98 (0.3)	1.31 (0.4)	0.59 (0.18)	0.98 (0.3)	1.64 (0.5)
Intermediate-Low	0.66 (0.20)	1.64 (0.5)	2.62 (0.8)	0.75 (0.23)	1.64 (0.5)	2.95 (0.9)
Intermediate	0.92 (0.28)	3.28 (1.0)	6.23 (1.9)	0.89 (0.27)	3.28 (1.0)	6.89 (2.1)
Intermediate-High	1.21 (0.37)	4.92 (1.5)	8.86 (2.7)	1.12 (0.34)	4.92 (1.5)	8.86 (2.7)
High	1.41 (0.43)	6.56 (2.0)	12.14 (3.7)	1.38 (0.42)	6.56 (2.0)	12.46 (3.8)

TABLE 1: Reproduction of Table 4 from the Front Matter of NCA5

Considering only projections representing processes quantified with at least medium confidence, IPCC AR6 assessed global mean sea level projections for all emissions scenarios (including implausible extreme emissions scenarios) for 2100 to fall between 0.2 and 1.6 m (5th–95th percentile range). Nevertheless, the range of sea level rise scenarios considered by NCA5 extends to 2.0 m. Further, NCA5 fails to include plausible lower scenarios, such as 0.2 m cited by the IPCC, which also corresponds to the average rate of sea level rise over the past century.

Chapter 9 of NCA5 offers the following predictions of sea level rise:

"Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2)."

The projected sea level rise values span from the Intermediate scenario to values slightly greater than the High scenario. They can be put into context by considering the [[HYPERLINK "https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level"](https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level)] global sea level rise from 2000-2024, which is only approximately 3.4 inches (0.28 feet). **NCA5 is thus projecting a sea level rise during 2025 and 2050 that is 3.5 to 5.8 times the rate observed during 2000-2024, an exceedingly implausible outcome.** Chapter 9 further states:

“Looking toward the future, an 11 inch (28 cm) average rise along the contiguous US coastline is expected by 2050 (relative to 2020), with a *likely* range of 9-13 inches.”

...

“There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (likely range of about 9–13 inches) between 2020 and 2050”

In summary, NCA5 presents future sea level rise scenarios that are not directly relatable to either SSP/RCP emissions scenarios or to plausible global warming levels. The NCA5 scenarios include two that are higher than the 95th percentile for the extreme emissions scenario RCP8.5 and include hypothesized ice sheet processes in which there is low confidence. Projections to 2050 require rates of sea level rise from 2025 to 2050 that are more than triple the rate observed during 2000-2024. Further, NCA5 ascribes *high confidence* to these sea level rise projections. CWG25 Section 7.3 provides further context for USGCRP projections of extraordinary sea level rise in the next 25 years.

More generally, NCA5’s inclusion of, and even focus on, implausible extreme scenarios supports projections of alarming impacts that are very unlikely to be driven by anthropogenic warming.

7 CONFLATION OF NATURAL AND ANTHROPOGENIC CLIMATE CHANGES

NCA5’s Glossary defines “climate change” as a change in climate for any reason. This is technically correct, but at variance with the (now) popular perception of all climate changes being anthropogenic. The distinction is not academic- it is central both to attribution questions and to projections, since anthropogenic changes would respond to mitigation, while natural changes are unavoidable.

The discussion on NCA5 page 2-4 begins “Human activities are changing the climate”, then goes on to list evidence for anthropogenic GHG emissions and climate warming. The next paragraph begins “Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970.” In context the implication is that the warming of CONUS faster than the planetary average is an effect of GHG emissions. But it is an artifact of the Earth’s surface being 70 percent ocean. Since the ocean warms more slowly than land, comparison of any land surface outside the tropics with the global average would show the land surface to be warming faster than the global average, regardless of the cause of the warming.

The same page goes on to say “Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018 although some estimates put heat-related mortality closer to 1,300 deaths annually.” But extreme heat, whether natural or not, has always been a risk to human health. As to trends, the data show that adaptation has caused the mortality burden of extreme heat to drop substantially in recent decades (CWG25 Section 10.3.1).

Consider also the NCA5 statement on precipitation that we cited in Section 3.2:

Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

The attribution is superfluous because the statement is a tautology by NCA5's definition of climate change. But its gratuitous inclusion effectively attributes the observed trend to greenhouse gas emissions.

Exploitation of the ambiguity in "climate change" is endemic to NCA5. The NASEM review (pp. 23-24) commented on this problem as follows:

The draft NCA5 report frequently describes "change" but does not consistently distinguish between natural variability and climate change. This lack of clarity can be misleading for the reader by creating the misconception that some impacts that are the result of the combination of natural variability and climate change are instead solely due to climate change... it is important for NCA5 authors to accurately identify the multiple drivers of change (including global change), in addition to climate change, and accurately attribute impacts. Clearly describing impacts due to natural variability, climate change, or a combination of the two is important not only for informing policy decisions, but also for building public understand and trust in the report's messages. Climate change and natural variability should be clearly defined in the glossary and natural variability could be introduced in chapter introductions when the concept is important for understanding key messages.

This could have been easily addressed by reserving the term "climate change" for anthropogenic changes and using "climate variability" for natural changes. But the NCA5 authors seemingly ignored their recommendation.

A separate but related issue is use of the term "climate change" to refer to increases in socioeconomic vulnerabilities that have anthropogenic but non-GHG-related causes. NCA5 page 1-19 states "Climate change exacerbates inequalities." But the issue discussed is the negative correlation between neighborhood-level income and land surface temperatures (LST) in urban areas. To the extent the correlation is real the most likely explanation is that low-income households concentrate where housing is less expensive, which may be in neighborhoods with less nearby parkland and tree cover, which has nothing to do with CO₂ emissions. Similarly the NCA5 makes repeated reference to the Billion Dollar Disaster dataset which is dominated by trends in population and economic growth, as we discussed in CWG25 Section 10.2.

8 SUMMARY EVALUATION OF NCA5 AND RECOMMENDATIONS FOR NCA6

This chapter summarizes our evaluation of NCA5 relative to OSTP's charge: whether NCA5 (1) complied with the USGCRP's statutory obligation; (2) adheres to the core tenets of Gold Standard Science; and (3) can suitably inform federal climate and energy policy. The points made in this summary analysis refer to specific sections of this report as well as to the CWG25 report.

8.1 Compliance with USGCRP's statutory obligation

As cited in Section 1.2 of this report, the Global Change Research Act requires an assessment that:

- (1) integrates, evaluates, and interprets the findings of the [Global Change Research] Program and discusses the scientific uncertainties associated with such findings;
- (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
- (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

We deem NCA5 to have fallen short when evaluated against these criteria because of the following major shortcomings (each is detailed in the chapters cited):

- Inadequate assessment of the relevant topics in climate science and the hazard components of climate impacts (such as hurricanes and floods). NCA5 instead focuses on evaluation of societal vulnerabilities (such as flood infrastructure, access to air conditioning, etc.), “Climate Action,” and policy recommendations with a social justice emphasis (Section 1.2).
- Overconfidence in conclusions and inadequate assessment of uncertainties (Section 3.1.5)
- Inadequate discrimination between natural and human-induced causes of trends and impacts (Chapter 7)
- Inadequate analysis of climate trends by relying on short time periods (Chapter 6)
- Uncritical evaluation of emission scenarios and climate simulations in making projections for the next 25 to 100 years (Chapter 6; Section 3.2.1 and Chapter 5 of CWG25).

8.2 Adherence to the tenets of Gold Standard Science

With respect to the tenets of Gold Standard science listed in Section 1.2 of this report, we have identified the following major shortcomings in NCA5:

- **Lack of reproducibility.** In the few examples that we examined closely, we identified an instance where we could not reproduce the findings of the NCA5, a task that should require only rudimentary data analysis (Section 4.1)
- **Lack of transparency.** In many instances, the Traceable Account fails to justify the Key Finding. Metadata was not readily accessible. (Chapter 5)
- **Inadequate communication of error and uncertainty.** The Traceable Account for each Key Message provides a section on Major Uncertainties and Research Gaps; most of the accounts that we examined were superficial and uninformative. (Chapter 5)
- **Not skeptical of findings and assumptions.** The main text of the chapters is, with few exceptions, not skeptical of its findings and assumptions. (Chapters 3, 5)
- **Some hypotheses and Key Messages are not falsifiable.** Key Message 13.4 is but one of many examples: “Equitable Distribution of Transportation Trade-offs and Benefits Requires Community Involvement.”
- **Failure to acknowledge benefits** of warming and additional atmospheric CO₂ (CWG25 Section 2.1, Chapter 9)
- **Inadequacy of the peer review process.** The review of the NCA5 Third Order Draft by National Academies of Science, Engineering and Medicine (NASEM) identified some of the deficiencies we have noted, but the NCA5 authors were not obligated to adopt the NASEM recommendations. More importantly, we’ve identified many other deficiencies in NCA5; the

NASEM review did not point them out and thus lacked the rigor expected of NASEM reports. (Section 1.4, Chapter 7)

8.3 Suitability for informing Federal climate and energy policy

We assess that the selection and presentation of information in NCA5 makes it an unreliable basis for U.S. climate and energy policymaking. For each of the elements of knowledge characterization suitable for risk management listed in Section 1.3, here are specific examples where NCA5 falls short:

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
 - NCA5 focused on implausibly extreme scenarios for emissions and sea level rise scenarios and made policy recommendations without adequate consideration of the costs
- The degree to which data/information exists and are reliable and relevant
 - NCA5's assumptions about model reliability, and its use of short time periods for analysis, does not support its high-confidence conclusions
- The degree to which there is disagreement among experts, including those from different environments or academic fields
 - While NCA5 was an interdisciplinary effort, the concerns we have raised all point to a failure to canvass or communicate the full range of evidence including data and research findings that speak against Key Messages.
- The degree to which the phenomena involved are understood and accurate models exist
 - NCA5 is not appropriately skeptical of the ability of climate models to attribute the causes of warming and extreme events or to project future climates
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns
 - A major NCA5 shortcoming is its dismissal of natural climate variability in many contexts where it should have been a major consideration

NCA5 is also problematic for informing policy because its hyperbolic language promotes alarm and advocates for specific policies without proper analysis of marginal costs and benefits. In recent decades, climate science has engendered passion and emotion. Indeed, some younger climate scientists have gone into the field to "save the planet." The NASEM Review of the NCA5 underscores the endemic nature of this problem - their review appears to be written by authors who share many of the biases of the NCA5 team, with an inordinate focus on social and policy issues. It is then not surprising that objectivity can suffer when climate scientists communicate their understanding to non-experts. Further, the field of climate science has been politicized by NetZero mandates. This lack of objectivity usurps the public's right to make informed choices and undermines their confidence in the scientific enterprise.

Philip Handler, President of the National Academy of Sciences, identified the problem forty-five years ago in an [[HYPERLINK "https://science.sciencemag.org/content/208/4448/1093"](https://science.sciencemag.org/content/208/4448/1093)] that still resonates:

Difficulty arises in the scientific community from confusion of the role of scientist *qua* scientist with that of scientist as citizen, confusion of the ethical code of the scientist with the obligation of the citizen, blurring the distinction between intrinsically scientific and

intrinsically political questions. When scientists fail to recognize these boundaries, their own ideological beliefs, usually unspoken, easily becloud seemingly scientific debate.

8.4 Recommendations for NCA6

While we have assessed NCA5 to be scientifically inadequate and unsuitable as a basis for decision-making, one can imagine a different National Climate Assessment that meets statutory and policymaker requirements. The goal should be not to persuade, but to impart understanding by being objective, transparent and complete. A suitable NCA would be an important complement to IPCC assessments to the extent that its analysis and conclusions differed from the oracular “consensus” of the IPCC reports and additional topics are addressed. Such a report would promote a more open scientific discussion and a more informed policy debate.

We recommend that the NCA6 have a narrower scope than NCA5, refocusing on climate science, including natural climate variability, with topics to include:

- How the climate has changed in the past. The U.S. has the best and longest meteorological records and they should be examined and displayed in their entirety. Trend analyses should include longest periods available and employ suitable statistical methods. Local paleoclimate data should be considered where available. Analysis should demonstrate not only how the climate has varied and changed, but also regional heterogeneity. Standard, easily understandable metrics should be employed.
- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future.
- A critical survey of current global and regional modeling capabilities and their suitability for regional impact assessments and projections. This would include an assessment of their ability to reproduce observed changes. It should also discuss alternative methods for generating projections and forecasts on regional and decadal scales, along the lines of Chapter 10 of the IPCC AR6 WGI Report.
- Assessment of the impacts of recent historical climate variability and change on ecosystems and society. Where long-term data indicate a detectable regional change, regional projections can be made for the period 2030-2050. Emissions scenarios exceeding RCP4.5/SSP2-4.5 and ECS values exceeding 4°C should not be used. Regional projections to 2100 have no credibility at this time.

It is important that climate projections be assessed in context of current science capabilities. The pressures toward spatially or temporally precise projections should be resisted as the current models are nowhere up to the task (an example is discussed in CWG25 Section 5.8). In that light, the many pages of NCA5 devoted to projected regional and sectoral impacts have little value.

Given the substantial deficiencies in NCA5 that we have identified, along with the endemic bias of the climate community towards alarmism and policy advocacy, producing an objective NCA6 report with the current NCA organizational construct would be a challenge. A NASEM review could help, but only if the selected participants reflect full viewpoint diversity and do not simply mirror the assumptions and biases of past NCA teams. We regard the CWG25 report to be a good start on NCA6 in terms of scope and objectivity, including adherence to the tenets of Gold Standard Science.

More broadly, we recommend a rewrite of the Global Change Research Act. The current mandate is vague and off point, allowing successive NCA teams to interpret the mandate as they see fit.

Moreover, it is becoming increasingly clear that current and foreseeable models are not fit-for-purpose to describe regional climates, let alone usefully project them for 25 and 100 years. Further, the use of the term “global change” is ambiguous and outdated.

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APPENDICES

APPENDIX 1: Charge to the review

ABOUT THE AUTHORS

[Insert updated bios]

Critique of the Fifth National Climate Assessment

[TOC \o "1-3" \h \z \u]

EXECUTIVE SUMMARY

This report critically evaluates the Fifth National Climate Assessment (NCA5), finding it an inadequate basis for climate and energy policies. A detailed review of the foundational chapters on climate science raises several key concerns:

Scientific Integrity

- An advocacy tone, particularly in the Overview chapter, that is inconsistent with scientific objectivity
- Framing climate as a morality play
- Endemic overconfidence when stating conclusions, including inflated certainty levels and overstatement of findings from underlying sources
- No mentions of dissent, disagreement, controversies, or tradeoffs

Flawed methodology

- Minimal discussion of observational inadequacies
- Use of short time periods for trend analyses; more generally lack of a consistent rule for choosing time scales
- Attribution is implied, not dissected
- Overemphasis on extreme scenarios for future emissions and sea level rise
- Inadequate traceable accounts to support key conclusions

Inadequate Review Process

- A review by the National Academy of Sciences, Engineering, and Medicine (NASEM) failed to challenge some fundamental flaws in NCA5
- The NCA5 authors failed to adopt some improvements recommended by NASEM

The report shows NCA5 to be a biased and incomplete picture of climate science that skews toward excessive climate risk. Consequently, NCA5 should not be used as basis for climate and energy policies.

Motivated optimism with an advocacy tone

Subtle advocacy with emphasis

Attribution is implied, not dissected

Framing climate as a morality play

Dissent is invisible

Minimal discussion of observational limitations

No mention of tradeoffs

Top of Form

1 INTRODUCTION

1.1 About this Report

This report responds to a request from the Office of Science and Technology Policy (OSTP) Director Michael Kratsios (reproduced in Appendix 1) that we assess the suitability of the Fifth National Climate Assessment (NCA5 2023) for informing climate and energy policies.

To conduct this assessment, we reviewed NCA5 itself, the National Academies of Science, Engineering and Medicine (NASEM) review of the Third Order NCA5 Draft, and the USGCRP responses to that review. We have drawn upon our long experience working on advisory reports, including for the NASEM, the Intergovernmental Panel on Climate Change (IPCC) and other organizations, as writers, reviewers and study leaders.

We find that NCA5 should not be relied on for policy making as it is an incomplete and misleading picture of our understanding of the changing climate and the risks it poses to the nation. NCA5 was selective and incomplete in its survey of climate science. Further, we have reviewed recent scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025, herein denoted “CWG25”). The overall effect of the biases and omissions of NCA5 is an excessively dire picture of climate risk.

To support our finding, the following sections of this chapter provide some background on the National Climate Assessments and the standards by which we have assessed NCA5. Chapters 2 through 7 detail important ways in which NCA5 fails to meet those standards. Finally, Chapter 8 summarizes our evaluation of NCA5 and makes recommendations for NCA6.

1.2 About the National Climate Assessments

The [[HYPERLINK "https://www.globalchange.gov/"](https://www.globalchange.gov/)] (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate “a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change.”

The National Climate Assessment (NCA) Reports evolved from the GCRA requirement to:

Prepare and submit to the President and the Congress an assessment which (1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

The five NCA Reports to date have interpreted this mandate in different ways:

- NCA1 (2000) was a multidisciplinary effort to study and portray in regional detail the potential effects of human-induced global warming on the United States.

- NCA2 (2009) was a relatively short report that not only focused on the potential consequences of climate change but also sought to identify potential adaptation measures and identify the highest priorities for future research.
- NCA3 (2014) was an expanded effort that continued along the lines of NCA2, and was distinguished by a comprehensive review process, including a review by the National Academy of Sciences. NCA3 introduced a traceability analysis for each key finding, including a description of uncertainties.
- NCA4 (2017/2018) was a further expanded effort that was published in two volumes: I Climate Science Special Report (CSSR), and II Impacts, Risk, and Adaptation in the United States. This was the first NCA report to devote significant effort to assessing climate science.
- NCA5 (2023) returned to a single volume format, reducing discussion of climate science to a cursory two chapters, with continuing focus on regional and sectoral impacts of climate change. NCA5 expanded its remit to topics that are arguably outside the purview of the USGCRP, focusing on “Climate Action” and policy recommendations with a social justice emphasis.

These successive interpretations of the NCA are poorly aligned with the GCRA’s statutory requirements. Only NCA4 gives serious consideration to climate science, which receives the great majority of USGCRP funding, and even then NCA4 misrepresents some important points. Natural climate variability is essentially dismissed as unimportant in NCA4 and barely mentioned in NCA5 in most contexts, despite the mandate to include both human-caused and natural climate change. Most significantly, NCA5 has redirected the focus away from climate science and even the hazard elements of impacts, towards evaluation of societal vulnerabilities and advocacy for particular policy options, especially deployment of wind and solar power generation.

1.3 Standards for Assessing NCA Products

Beyond the statutory requirements stated above, another pertinent standard is President Trump’s executive order of May 23, 2025, [[HYPERLINK "https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/"](https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/)]. It enumerates some of the characteristics of good science, namely that it should be:

- i. reproducible;
- ii. transparent;
- iii. communicative of error and uncertainty;
- iv. collaborative and interdisciplinary;
- v. skeptical of its findings and assumptions;
- vi. structured for falsifiability of hypotheses;
- vii. subject to unbiased peer review;
- viii. accepting of negative results as positive outcomes; and
- ix. without conflicts of interest.

For an assessment of policy relevant science, it is also important to include statements about the strength of knowledge. The IPCC’s approach to assessing strength of knowledge is based on judgment of the available evidence and agreement among experts. But there are more sophisticated knowledge characterizations for risk management. Here are the elements according to Aven (2017):

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
- The degree to which data/information exists and are reliable and relevant
- The degree to which there is disagreement among experts (including those from different environments or academic fields)
- The degree to which the phenomena involved are understood and accurate models exist
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns (issues that are known to matter but are ignored, such as, in this context, natural variability).

2 NCA5 OVERVIEW CHAPTER: ADVOCACY LANGUAGE AND UNSCIENTIFIC TONE

NCA5 Chapter 1, “Overview”, holds a prominent place in the Report since it summarizes the entire report and is the only section that many will read. Chapter 1 is marred by an activist tone, language that aggressively promotes mitigation policies, and motivated optimism. As such, this chapter adds an imprimatur of scientific authority to naïve and simplistic declarations of opinion about public policy. Some examples are presented here.

Chapter 1 opens as follows:

The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases.

This statement presupposes that all warming is anthropogenic, that all warming is bad and causes economic damage, and that warming intensifies extreme weather. Such sweeping generalizations go well beyond what science has or can establish. The statement also refers to growing risks without reference to their magnitude – a small risk that grows may still be a small risk, and a large risk may be only incrementally worsened.

On the next page the Overview states:

Each additional increment of warming leads to greater risks [here it lists 7 key components of society including food security and the economy]... Without deeper cuts in global net emissions, climate risks to the US will continue to grow... Action to limit future warming and reduce risks can have near-term benefits and opportunities: low-carbon energy jobs, Improved air quality, Health benefits, Economic benefits...”

The authors write as if climate policy does not involve trade-offs and all measures to reduce future warming will be effective and beneficial. Neither the vast body of scholarship on climate science and economics, nor historical experience, support such simplistic claims (CWG25). Not every additional increment of warming leads to economic harms; in fact, NCA5 Chapter 19 acknowledges that there

will also be benefits. Nor is climate policy guaranteed to benefit the economy; it could impose net costs. Such misleading statements are a disservice to policymakers.

Pages 8 and 9 of the Overview promote renewable energy options by noting, correctly, that the leveled costs of wind/solar generation have fallen sharply since 2010, and so offers this rationale for pursuing deep emission reductions:

Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources.

Yet it has long been known that intermittent renewables generation must be supplemented by dispatchable generation to meet grid reliability standards, and that doing so (e.g., through natural gas, fission, or storage) significantly increases the cost of electricity. Further, there are yet unmet synchronization challenges in electrical grids with heavy penetration of wind and solar generation. NCA5 fails to acknowledge these facts. But more importantly, we see no reason for NCA5 to be discussing renewable energy technologies and economics in the context of its mandate.

Page 17 of the Overview introduces the discussion of risks from extreme weather events by saying “Harmful impacts from more frequent and severe extremes are increasing across the country.” This creates the impression that extreme weather events are worsening and that disaster losses are driven by trends in extreme weather. While the section goes on to acknowledge that some of the increase is due to increases in the exposure and value of assets at risk, it then invokes the NOAA Billion Dollar Dataset as evidence of extreme weather getting worse. Scientists have shown that this is an invalid metric (CWG2025 Section 10.2) since it measures the growth of the economy not the frequency of extreme weather, and indeed NOAA has recently withdrawn the data product. Even though the dataset was still distributed by NOAA at the time of the NCA5, the report authors failed to assess it skeptically and see that it was unfit for the purpose of measuring climate trends.

Page 23 of the Overview states, in large font:

Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities.

It is pointless to try to evaluate this statement on scholarly grounds. This kind of language doesn’t belong in a scientific assessment report. Its prominent inclusion points not only to the willingness of NCA5 authors to promote alarm, but also the ineffectiveness of the review process in eliminating such statements.

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS

3.1 Inflated certainty levels

Overconfidence in stating conclusions has been an endemic problem in NCA Reports. The authors frequently make sweeping generalizations without appropriate caveats or acknowledging uncertainties. The overconfidence begins with inflated language to describe certainty levels.

NCA5 uses specific terms to convey information about scientific confidence associated with important finds, observations and projections. The Front Matter of NCA5 states that

confidence in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.

Table 1 from the Front Matter provides calibrated language for confidence assessment:

Very high:	Strong evidence (established theory, multiple sources, well documented and accepted methods, etc.). High consensus
High:	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.). Medium consensus
Medium:	Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) Competing schools of thought.
Low:	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.). Disagreement or lack of opinions among experts.

This terminology is obviously inflated: *high confidence* with just moderate evidence and medium consensus; *medium confidence* with only suggestive evidence and competing schools of thought. This inflation in terminology leads to overconfidence in conclusions.

Even with this inflated terminology, NCA5 further inflates the confidence level of many of its conclusions to well beyond what the IPCC has concluded with more thorough justification, and by incorrectly applying its own standards. An example is the conclusion about anthropogenic influence on climate change, arguably one of the most important scientific statements of the report.

Key Message 3.1 Traceable Account states:

There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused *all* global warming observed over the industrial era.

while the corresponding statements from IPCC AR5 and AR6 are

AR5: It is *extremely likely* that *more than half* of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. (IPCC, 2013)

AR6: The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.

The IPCC AR5 and AR6 statements provide likelihood assessments but not a confidence level. While NCA5 claims with *very high confidence* that fossil fuels have unequivocally caused *all* global warming, AR5 refers to “*more than half* of the observed warming” and AR6 provides a more nuanced statement that relates to a *likely* range of warming contributed to by human drivers.

3.2 Overstating findings in underlying sources

Although we did not do a detailed audit of NCA5’s use of source material, spot checks suggest a pattern of overstatement.

Chapter 2 page 11 reports on an increase in precipitation in some areas and attributes it to “climate change”:

Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

NCA5 attributes the claim to Knutson and Zeng (2018). But Knutson and Zeng did not say these things nor did they analyze this particular period. For 1981-2010 they cautioned that observed changes are consistent with natural variability, and they did not claim attributable trends were observed over the United States.

As another example of overstating findings, NCA5’s Chapter 2 page 18 states

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.

This is apparently attributed to Diffenbaugh *et al.* (2018) and Kirchmeier-Young and Zhang (2020). Diffenbaugh *et al.* presented ratios of observed occurrences of extreme events to simulated occurrence rates in CMIP6 models run with only natural forcings. They report that for 79% of the U.S., extreme rainfall events are currently more frequent than in simulations, and the ratio of occurrences will rise under future warming simulations. This is not “robust” evidence of anthropogenic influence since it requires readers to assume that climate models accurately simulate regional precipitation patterns, something that the IPCC AR6 states is uncertain (AR6 WGI SPM Box SPM 1.2, SPM Section C.1.3).

Kirchmeier-Young and Zhang used three global climate models to analyze extreme 1- and 5-day events in North America. They noted large differences among the three models in their simulated precipitation changes, and two of the three models failed to yield attribution for 5-day events for the North America mean. In other words, the models disagreed on whether the observed changes were anthropogenic. Both of the cited references utilized the implausible RCP8.5 scenario (Chapter 6 of this Report) and began their “historical” observational records only in 1961. Here again this is not “robust” evidence, it is merely suggestive, particularly since other studies have found natural variability to be predominant.

3.3 Example: Emergent constraints

Some of the overconfidence expressed by NCA5 arises by omitting discussion of counterevidence in the peer reviewed literature, ignoring dissent and disagreement. An example is the topic of “emergent constraints”. NCA5 Chapter 3 page 17 invokes this concept to support its claim that key uncertainties in climate model projections have been reduced:

An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as “emergent constraints.” The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship.

Emergent constraints appeared in the climate modeling literature as an attempt to tie climate model behavior to climate observations in hopes of generating insight into real-world equilibrium climate sensitivity to a doubling of carbon dioxide (ECS). Climate models exhibit a wide range of ECS values. The idea of emergent constraints is to examine whether the models with shared sensitivity values also share a common representation of some climate process (usually related to clouds) that might influence ECS. Suppose, for instance, that in low-ECS models the total cloud fraction in the tropics is strongly correlated with that in the southern midlatitudes, but in high-ECS models the correlation is weak. Then researchers could examine whether the observed correlation is strong or weak and draw a conclusion about which type of model, and therefore which ECS value, is more likely.

A problem in the emergent constraint literature is that there has been a proliferation of proposed correlations with little physical motivation. NCA5 alludes to this in the Traceable Accounts section (p. 3-40) but not in the main Chapter text. As shown by Schlund *et al.* (2020) many emergent constraints patterned on CMIP5 models (Coupled Model Intercomparison Project No. 5, used for the IPCC 5th Assessment Report) failed to work on CMIP6 models (used for the IPCC 6th Assessment Report). In other words, the observed correlations in CMIP5 models between ECS and cloud processes failed to show up in CMIP6 models, indicating that they were likely spurious rather than clues to physical processes governing the climate system. As a result, emergent constraints estimated on CMIP5 models *increased* the uncertainty of ECS, rather than decreasing it as intended and as claimed by NCA5.

Yet NCA5 described the use of emergent constraint analysis as an advance that reduced uncertainty of ECS and climate model projections (p. 3-38):

Emergent constraints have been widely applied to reduce the simulated spread in the climate feedbacks that shape climate sensitivity.

4 ARBITRARY AND AMBIGUOUS TREND ANALYSIS

CWG25 Chapter 6 discussed the need for care in the choice of time scale when making claims about trends in extreme weather. We provided examples from analysis of river flooding, heatwaves, and extreme precipitation to show how assertions about apparent trends based on short data sets fall apart when looking at longer versions of the same data sets. NCA5 uses varying time periods for trend analyses, especially in Chapter 2 (which is focused on trends), without explaining why shorter or longer intervals were chosen. For example, page 2-4 defines temperature trends with respect to the interval since the late 1800s whereas page 3-29 presents temperature trends over 1972-2021. Page 2-11 compares rainfall over the 2002-21 versus 1901-1960 intervals while page 2-18 uses the interval since the late 1950s to compute trends.

A further problem is that NCA5 uses term “trend” repeatedly without indicating if it is statistically significant (*i.e.* distinguishable from random variability); the ambiguity creates the impression all the observed changes were significant, but readers are left to speculate. All climate variables will, in principle, drift up or down over any particular time interval. Identifying the change as a trend requires showing that it is statistically significant using a variance estimator suitable for the type of data being analysed. Of particular importance is choosing a method robust to serial correlation which is frequently present in climate data. Throughout Chapters 1 to 3, references are made to “trends” without explaining how they were computed. The exception was on page 1-19 which refers to urban temperature trends being calculated using the Theil-Sen estimator, although that method does not seem to have been used elsewhere. The one case where reference is made to statistical significance was on Page 2-9 referring to a trend in Atmospheric Optical Depth, but no explanation is given of how significance was determined. Page 2-19 refers to regional trends in droughts being “robust” but again fails to explain how the term was defined.

In this chapter when we refer to calculation of trends in precipitation, we use ordinary least squares to compute the linear trend over the entire sample length and we use the Vogelsang and Franses (2007) variance estimator which is robust to general forms of serial correlation.

4.1 Average and Extreme Precipitation

CWG25 Section 6.4 we presented analyses of updated data for the same locations (and many others), in all cases finding both considerable regional heterogeneity and that trends detectable on one time scale are often not detected on longer or shorter time scales. These findings argue against simple attribution of changes to anthropogenic influences.

NCA5 did not continue the NCA4 precedent of using the post-1901 interval as the time scale for its precipitation discussion. Instead it refers to changes “since the 1950s”; NCA5 Figure 2.8 suggests 1958 might be the intended start date. Under Key Message 2.2 “Extreme Events Are Becoming More Frequent and Severe” (p. 2-16) NCA5 states (p. 2-18):

Rainfall is becoming more extreme
Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US. This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity.

In addition to our concerns that inferences about trends are contingent on choice of time scale, if the intended meaning of this statement is that positive and significant trends are found in heavy precipitation events across CONUS we cannot reproduce it. Details of our analysis can be found at [LINK TO BRIEF WRITEUP ON THIS](#) can we just reference CWG HERE

Based upon our analysis, the following is a more accurate summary of what U.S. precipitation data show.

There are regionally heterogeneous changes in average and extreme precipitation. Positive trends in annual average rainfall and extreme events (defined either as the annual maximum or the number of exceedances of the 99th percentile value) are generally weak or non-existent when looking at samples exceeding 130 years in length. Significant trends can be found when beginning the sample in the 1950s although in most cases the trends weaken and become

insignificant when looking at the post-1980 interval. This argues against attribution of changes in precipitation to anthropogenic warming.

4.2 Heatwaves

In contrast to NCA5, NCA4 examined heat extremes across the entire 20th century, pointing out that peak heat wave activity was reached in the 1930s and has decreased since then, and that recent increases are confined to areas west of the Rockies. NCA4 stated:

[The] warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]).

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s. (NCA4 pp. 190-191)

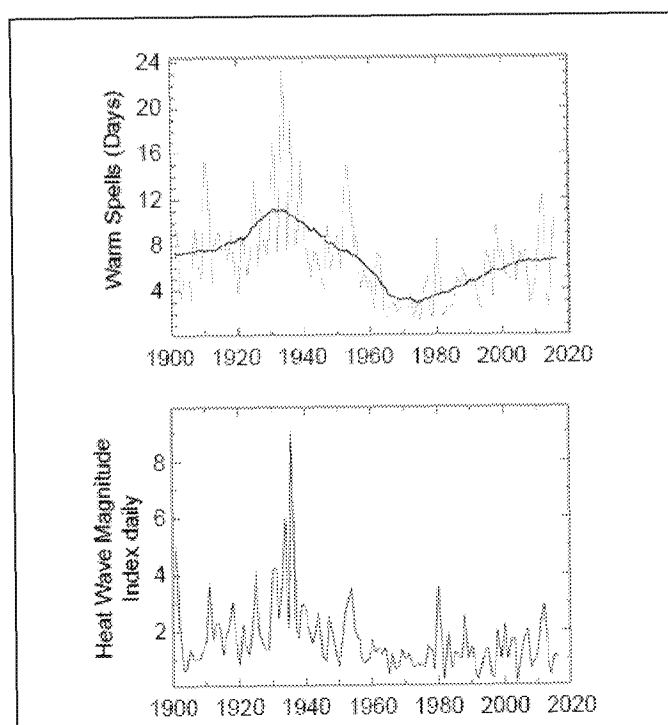


FIGURE 3. U.S. Heatwaves since 1900. Reproduction of NCA4 Figure 6.4

Contrast this careful and factual language from NCA4 with NCA5 Key Message 2.2: “Extreme Events Are Becoming More Frequent and Severe.” This blanket statement is followed by NCA5 Figure 2.7 (reproduced as Figure 4 below) which shows the number of hot days, cold days and warm nights

(respectively in panels a—c) over the period 2002-2021 compared to 1901-1960. [Presumably these are annual counts, although not stated in the caption.]

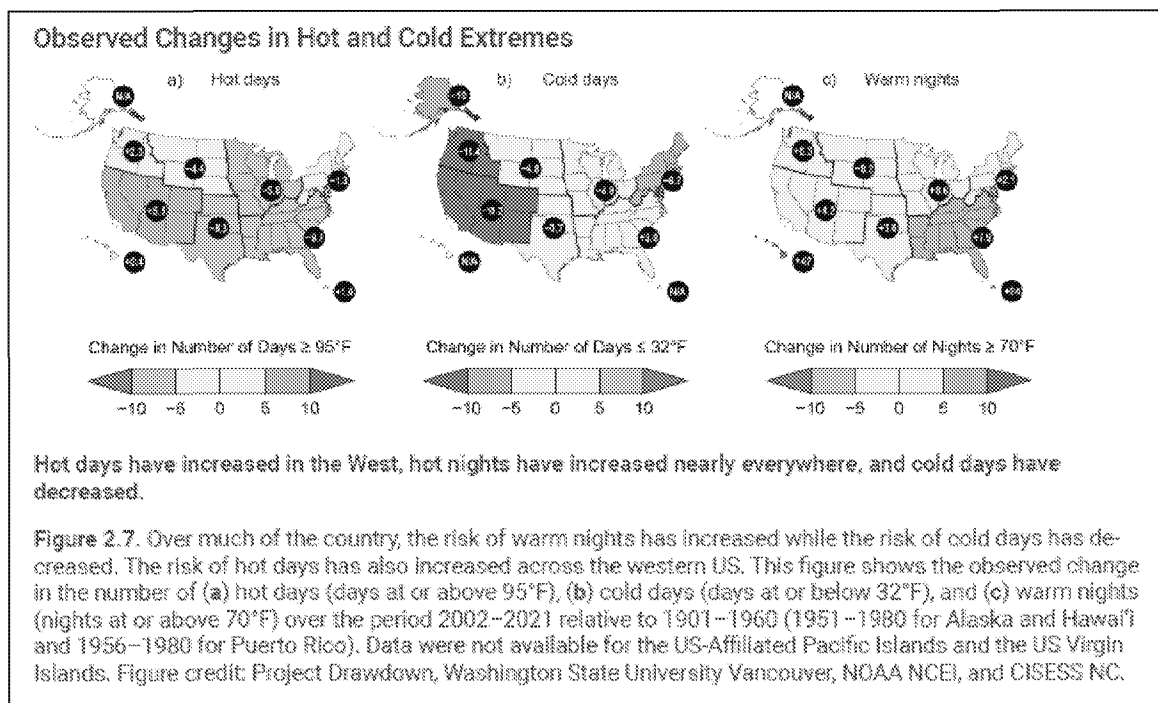


FIGURE 4: Reproduction of NCA5 Figure 2.7.

Close inspection shows that this figure actually contradicts the NCA5 Key Message with respect to heatwaves and instead reinforces the position of NCA4. Notwithstanding Key Message 2.2, the leftmost panel in NCA5 Figure 2.7 above shows that over most of CONUS the number of extreme heat days has *decreased* in recent decades compared to the prior century.

The accompanying discussion in NCA5 becomes convoluted as it appears to be aimed at supporting the Key Message despite the contrary evidence. NCA5 Chapter 2 elaborates on Key Message 2.2 by stating (page 16):

Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*).

But while it mentions the increase in hot days in the West, it fails to mention the decrease everywhere east of the Rockies. On the next page (page 17) it raises the comparison to the 1930s and then switches to discussing global counts:

By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s. ... Globally such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends.

The reference to a global trend seems to be an attempt to tie heatwaves to anthropogenic climate change. But the obvious question, unaddressed by NCA5, is why one region follows the global pattern of increasing heatwaves while most of the country is trending in the opposite direction. These issues

are addressed in Chapter 6 of CWG25, demonstrating that the range and magnitude of extreme temperatures are driven more by natural variability than by the small anthropogenic forcing. The analysis in CWG25 shows that for both (a) hot days ($\geq 95^{\circ}\text{F}$) and (b) number of days in heatwaves, the current decade is no hotter than a century ago in the U.S. Thus, the NCA5 claim that “multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades,” is simply false when expanding the temporal and spatial domains to encompass all available data (Chapter 6 and Figure 6.3.6 of CWG25).

NCA5 then pointed to the dramatic Pacific Northwest heatwave of 2021. CWG2025 Section 8.6.1 discussed this event in detail, reviewing the multiple peer reviewed studies that explained the unusual meteorological context was unrelated to human-caused climate change, a point omitted from the NCA5 discussion.

NCA5 finally addresses the declining heatwave trend in CONUS east of the Rockies but attempts to reframe it by focusing on urban warm spells.

[The] number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades. Across 50 large US cities, the US Global Change Research Program heatwave indicator ([[HYPERLINK "https://www" \].globalchange.gov/indicators/heat-waves\) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.](https://www.globalchange.gov/indicators/heat-waves)

We discussed this part of NCA5 in CWG25 Section 6.3. The figure referenced by NCA5 uses a short time period which begins in the 1960s, the coldest decade in the last 100 years, thus suppressing any comparison to the 1930s. Further, nighttime temperatures in urban areas have increased faster than daytime temperatures (which NCA5 acknowledges), but this is a signature of urban heat islands and not a good metric of climate change. CWG25 found that the occurrence of hot days ($\geq 95^{\circ}\text{F}$) has recently increased in the West, but declined in the remainder of the country, and in the nationwide average, since 1899.

5 INADEQUATE TRACEABLE ACCOUNTS

NCA3 began the practice of including a section on Traceable Accounts at the end of each chapter. This is the description from NCA5:

Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team’s expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

The Traceable Accounts for each Key Message includes the following sections:

- Description of Evidence Base
- Major Uncertainties and Research Gaps
- Description of Confidence and Likelihood

The Traceable Accounts could have addressed the statutory requirement that the NCA discuss scientific uncertainties. They could also help satisfy the Executive Order for Restoring Gold Standard Science by addressing reproducibility, transparency, communication of error and uncertainty, and skepticism of findings and assumptions. However, the Traceable Accounts in NCA5's Chapters 2 and 3 are uneven, often superficial and uninformative.

An example of a deficient Traceable Account is NCA5's Key Message 2.2: "Extreme Events are Becoming More Frequent and Severe". The "Description of the Evidence Base" offers two paragraphs, the first summarizing the findings and the second generically describing the types of data that can be used for storms. "Major Uncertainties and Research Gaps" focuses on the uneven distribution across U.S. populations due to differences in exposure and vulnerability. The only limitations in data referred to are the lack of a long-term record of lightning and the lack of homogenized daily and hourly temperature data apart from reanalysis products.

But the most astonishing deficiency is in the "Description of Confidence and Likelihood." One of the statements in Key Message 2.2 is:

Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*).

The Description of Confidence and Likelihood includes the following statement:

Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have high confidence that storms are delivering more rainfall and high confidence that storm surges are becoming higher.

No reference to journal publications or a specific data set is made anywhere in the chapter regarding hurricane-induced precipitation or storm surge to support this *high confidence* conclusion.

The Traceable Accounts for the various Key Findings of Chapter 3 have some substantial inconsistencies. Consider

Key Message 3-1: Human activities have caused global warming.
Confidence and Likelihood: "There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have *unequivocally* caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over this period."

The Uncertainties section addresses only uncertainties in radiative forcing by greenhouse gases, ignoring the great uncertainty in model response (CWG25 Chapters 4&5) In contrast, the Traceability Analysis of Key Message 3-4 ("Humans Are Changing Earth System Processes") raises

the problem that relatively little is known about the role of natural variability at the regional scale. From its Description of Evidence Base:

In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals.

And from its Major Uncertainties and Research Gaps:

For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

These statements are among the most scientifically credible in the entire NCA5 and they directly undercut the confidence assigned to Key Message 3-1.

There is also a generic problem in tracing NCA5's Traceable Accounts. The Front Matter of NCA5 states:

Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation.

Clicking on the 'eyeball' icon does not reveal the metadata information; instead a "Contact Us" email appears, addressed to the USGCRP. This is an inadequate way to archive the metadata information.

In summary, the Traceable Analyses examined here, with few exceptions, fail to meet the stated objectives of the NCA.

6 OVEREMPHASIS ON EXTREME SCENARIOS

To respond to the GCRA mandate to "project major trends for the subsequent 25 to 100 years," NCA5 relies on projections of future climate change based on estimates of future emissions (the so-called SSP scenarios) and/or specified levels of radiative forcing (the RCP scenarios). For the most part, NCA5 uses scenarios developed for the IPCC Assessment Reports.

CWG25 Section 3.2.1 presented a critical assessment of past and current IPCC scenario envelopes, showing that they have tended to overshoot observed emissions. IPCC AR6 published in 2021 stated that "The likelihood of high-emission scenarios like RCP8.5 and SSP5-8.5 is considered low in light of recent energy sector developments." and that same year UN Climate Negotiators (COP) stopped using scenarios above 4.5.

NCA5 makes the following observations about the scenarios they use:

NCA5 authors were advised to assess the full range of scenarios available. (Front Matter)

Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that the highest scenario, SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency. (Key Message 3.3 Traceable Analysis)

Despite acknowledging the issue, NCA5 otherwise ignored the problem. A keyword search of NCA5 of mentions of RCP/SSP scenarios finds over 50% referred to the extreme emissions scenarios RCP8.5/SSP5-8.5. Further, nine NCA5 figures (5.2, 6.9, 7.4, 11.3, 14.6, 22.13, 22.19, 27.9, 29.13) included *only* the 8.5 scenarios.

The problem of relying on extreme scenarios is particularly acute for NCA5's sea level rise projections. The sea level rise scenarios used in NCA5 do not relate directly to the SSP emissions scenarios, but rather to specified amounts of sea level rise by 2100. Table 4 of NCA5's "Guide to Using this Report" reproduced below shows that Low relates to 0.3 m (0.98 feet), Intermediate-Low relates to 0.5 m (1.64 feet), Intermediate relates to 1.0 m (3.28 feet), Intermediate-High relates to 1.5 m (4.92 feet), and High relates to 2.0 m (6.56 feet).

Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5						
Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2022."						
Sea Level Rise Scenario Descriptor	Global Mean Sea Level			United States		
Year	2050	2100	2150	2050	2100	2150
Low	0.49 (0.15)	0.98 (0.3)	1.31 (0.4)	0.59 (0.18)	0.98 (0.3)	1.64 (0.5)
Intermediate-Low	0.66 (0.20)	1.64 (0.5)	2.62 (0.8)	0.75 (0.23)	1.64 (0.5)	2.95 (0.9)
Intermediate	0.92 (0.28)	3.28 (1.0)	6.23 (1.9)	0.89 (0.27)	3.28 (1.0)	6.89 (2.1)
Intermediate-High	1.21 (0.37)	4.92 (1.5)	8.86 (2.7)	1.12 (0.34)	4.92 (1.5)	8.86 (2.7)
High	1.41 (0.43)	6.56 (2.0)	12.14 (3.7)	1.38 (0.42)	6.56 (2.0)	12.46 (3.8)

TABLE 1: Reproduction of Table 4 from the Front Matter of NCA5

Considering only projections representing processes quantified with at least medium confidence, IPCC AR6 assessed global mean sea level projections for all emissions scenarios (including implausible extreme emissions scenarios) for 2100 to fall between 0.2 and 1.6 m (5th–95th percentile range). Nevertheless, the range of sea level rise scenarios considered by NCA5 extends to 2.0 m. Further, NCA5 fails to include plausible lower scenarios, such as 0.2 m cited by the IPCC, which also corresponds to the average rate of sea level rise over the past century.

Chapter 9 of NCA5 offers the following predictions of sea level rise:

“Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2).”

The projected sea level rise values span from the Intermediate scenario to values slightly greater than the High scenario. They can be put into context by considering the [HYPERLINK "https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level"] global sea level rise from 2000-2024, which is only approximately 3.4 inches (0.28 feet). NCA5 is thus projecting a sea level rise during 2025 and 2050 that is 3.5 to 5.8 times the rate observed during 2000-2024, an exceedingly implausible outcome. Chapter 9 further states:

“Looking toward the future, an 11 inch (28 cm) average rise along the contiguous US coastline is expected by 2050 (relative to 2020), with a *likely* range of 9-13 inches.”

...

“There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (likely range of about 9–13 inches) between 2020 and 2050”

In summary, NCA5 presents future sea level rise scenarios that are not directly relatable to either SSP/RCP emissions scenarios or to plausible global warming levels. The NCA5 scenarios include two that are higher than the 95th percentile for the extreme emissions scenario RCP8.5 and include hypothesized ice sheet processes in which there is low confidence. Projections to 2050 require rates of sea level rise from 2025 to 2050 that are more than triple the rate observed during 2000-2024. Further, NCA5 ascribes *high confidence* to these sea level rise projections. CWG25 Section 7.3 provides further context for USGCRP projections of extraordinary sea level rise in the next 25 years.

More generally, NCA5’s inclusion of, and even focus on, implausible extreme scenarios supports projections of alarming impacts that are very unlikely to be driven by anthropogenic warming.

7 CONFLATION OF NATURAL AND ANTHROPOGENIC CLIMATE CHANGES

NCA5’s Glossary defines “climate change” as a change in climate for any reason. This is technically correct, but at variance with the (now) popular perception of all climate changes being anthropogenic. The distinction is not academic- it is central both to attribution questions and to projections, since anthropogenic changes would respond to mitigation, while natural changes are unavoidable.

The discussion on NCA5 page 2-4 begins “Human activities are changing the climate”, then goes on to list evidence for anthropogenic GHG emissions and climate warming. The next paragraph begins “Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970.” The implication is that the warming of CONUS faster than the planetary average is an effect of GHG emissions. But it is an artifact of the Earth’s surface being 70 percent ocean. Since the ocean warms more slowly than land, comparison of any land surface outside the tropics with the global average would show the land surface to be warming faster than the global average, regardless of the cause of the warming.

The same page goes on to say “Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018 although some estimates put heat-related mortality closer to 1,300 deaths annually.” But extreme heat, whether natural or not, has always been a risk to human health. As to trends, the data

show that adaptation has caused the mortality burden of extreme heat to drop substantially in recent decades (CWG25 Section 10.3.1).

Consider also the NCA5 statement on precipitation that we cited in Section 3.2:

Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

The attribution is superfluous because the statement is a tautology by NCA5's definition of climate change. But its gratuitous inclusion effectively attributes the observed trend to greenhouse gas emissions.

Exploitation of the ambiguity in "climate change" is endemic to NCA5. The NASEM review (pp. 23-24) commented on this problem as follows:

The draft NCA5 report frequently describes "change" but does not consistently distinguish between natural variability and climate change. This lack of clarity can be misleading for the reader by creating the misconception that some impacts that are the result of the combination of natural variability and climate change are instead solely due to climate change... it is important for NCA5 authors to accurately identify the multiple drivers of change (including global change), in addition to climate change, and accurately attribute impacts. Clearly describing impacts due to natural variability, climate change, or a combination of the two is important not only for informing policy decisions, but also for building public understand and trust in the report's messages. Climate change and natural variability should be clearly defined in the glossary and natural variability could be introduced in chapter introductions when the concept is important for understanding key messages.

This could have been easily addressed by reserving the term "climate change" for anthropogenic changes and using "climate variability" for natural changes. But the NCA5 authors seemingly ignored their recommendation.

A separate but related issue is use of the term "climate change" to refer to increases in socioeconomic vulnerabilities that have anthropogenic but non-GHG-related causes. NCA5 page 1-19 states "Climate change exacerbates inequalities." But the issue discussed is the negative correlation between neighborhood-level income and land surface temperatures (LST) in urban areas. To the extent the correlation is real, the most likely explanation is that low-income households concentrate where housing is less expensive, which may be in neighborhoods with less nearby parkland and tree cover, which has nothing to do with CO₂ emissions.

8 SUMMARY EVALUATION OF NCA5 AND RECOMMENDATIONS FOR NCA6

This chapter summarizes our evaluation of NCA5 relative to OSTP's charge: whether NCA5 (1) complied with the USGCRP's statutory obligation; (2) adheres to the core tenets of Gold Standard Science; and (3) can suitably inform federal climate and energy policy. The points made in this summary analysis refer to specific sections of this report as well as to the CWG25 report.

8.1 Compliance with USGCRP's statutory obligation

As cited in Section 1.2 of this report, the Global Change Research Act requires an assessment that:

- (1) integrates, evaluates, and interprets the findings of the [Global Change Research] Program and discusses the scientific uncertainties associated with such findings;
- (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
- (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

We deem NCA5 to have fallen short when evaluated against these criteria because of the following major shortcomings (each is detailed in the chapters cited):

- Inadequate assessment of the relevant topics in climate science and the hazard components of climate impacts (such as hurricanes and floods). NCA5 instead focuses on evaluation of societal vulnerabilities (such as flood infrastructure, access to air conditioning, etc.), “Climate Action,” and policy recommendations with a social justice emphasis (Section 1.2).
- Overconfidence in conclusions and inadequate assessment of uncertainties (Section 3.1.5)
- Inadequate discrimination between natural and human-induced causes of trends and impacts (Chapter 7)
- Inadequate analysis of climate trends by relying on short time periods (Chapter 6)
- Uncritical evaluation of emission scenarios and climate model simulations in making projections for the next 25 to 100 years (Chapter 6; Section 3.2.1 and Chapter 5 of CWG25).

8.2 Adherence to the tenets of Gold Standard Science

With respect to the tenets of Gold Standard science listed in Section 1.2 of this report, we have identified the following major shortcomings in NCA5:

- **Lack of reproducibility.** In the few examples that we examined closely, we identified an instance where we could not reproduce the findings of the NCA5, a task that should require only rudimentary data analysis (Section 4.1)
- **Lack of transparency.** In many instances, the Traceable Account fails to justify the Key Finding. Metadata was not readily accessible. (Chapter 5)
- **Inadequate communication of error and uncertainty.** The Traceable Account for each Key Message provides a section on Major Uncertainties and Research Gaps; most of the accounts that we examined were superficial and uninformative. (Chapter 5)
- **Not skeptical of findings and assumptions.** The main text of the chapters is, with few exceptions, not skeptical of its findings and assumptions and does not mention dissent or disagreement. (Chapters 3, 5)
- **Some hypotheses and Key Messages are not falsifiable.** Key Message 13.4 is but one of many examples: “Equitable Distribution of Transportation Trade-offs and Benefits Requires Community Involvement.”
- **Failure to acknowledge benefits** of warming and additional atmospheric CO₂ (CWG25 Section 2.1, Chapter 9)
- **Inadequacy of the peer review process.** The review of the NCA5 Third Order Draft by National Academies of Science, Engineering and Medicine (NASEM) identified some of the deficiencies we have noted, but the NCA5 authors were not obligated to adopt the NASEM

recommendations. More importantly, we've identified many other deficiencies in NCA5; the NASEM review did not point them out and thus lacked the rigor expected of NASEM reports.

8.3 Suitability for informing Federal climate and energy policy

We assess that the selection and presentation of information in NCA5 makes it an unreliable basis for U.S. climate and energy policy making. For each of the elements of knowledge characterization suitable for risk management listed in Section 1.3, here are specific examples where NCA5 falls short:

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
 - NCA5 focused on implausibly extreme scenarios for emissions and sea level rise scenarios and made policy recommendations without adequate consideration of the costs
- The degree to which data/information exists and are reliable and relevant
 - NCA5's unjustified assumptions about model reliability, and its use of short time periods for analysis, does not support its high-confidence conclusions
- The degree to which there is disagreement among experts, including those from different environments or academic fields
 - While NCA5 was an interdisciplinary effort, the concerns we have raised all point to a failure to canvass or communicate the full range of evidence including data and research findings that speak against Key Messages.
- The degree to which the phenomena involved are understood and accurate models exist
 - NCA5 is not appropriately skeptical of the ability of climate models to attribute the causes of warming and extreme events or to project future climates
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns
 - A major NCA5 shortcoming is its dismissal of natural climate variability in many contexts where it should have been a major consideration

NCA5 is also problematic for informing policy because its hyperbolic language promotes alarm and advocates for specific policies without a proper risk analysis. The NASEM Review of the NCA5 underscores the endemic nature of this problem - their review appears to be written by authors who share many of the biases of the NCA5 team, with an inordinate focus on social and policy issues. It is then not surprising that objectivity can suffer when climate scientists communicate their understanding to non-experts. Further, the field of climate science has been politicized by NetZero mandates. This lack of objectivity usurps the public's right to make informed choices and undermines their confidence in the scientific enterprise.

Philip Handler, President of the National Academy of Sciences, identified the problem forty-five years ago in an [[HYPERLINK "https://science.sciencemag.org/content/208/4448/1093"](https://science.sciencemag.org/content/208/4448/1093)] that still resonates:

Difficulty arises in the scientific community from confusion of the role of scientist *qua* scientist with that of scientist as citizen, confusion of the ethical code of the scientist with the obligation of the citizen, blurring the distinction between intrinsically scientific and intrinsically political questions. When scientists fail to recognize these boundaries, their own ideological beliefs, usually unspoken, easily becloud seemingly scientific debate.

8.4 Recommendations for NCA6

While we have assessed NCA5 to be scientifically inadequate and unsuitable as a basis for decision-making, one can imagine a different National Climate Assessment that meets statutory and policy maker requirements. The goal should be not to persuade, but to impart understanding by being objective, transparent and complete. A suitable NCA would be an important complement to IPCC assessments to the extent that its analysis and conclusions differ from the “consensus” of the IPCC reports and additional topics are addressed. Such a report would promote a more open scientific discussion and a more informed policy debate.

We recommend that the NCA6 have a narrower scope than NCA5, refocusing on climate science, including natural climate variability, with topics to include:

- How the climate has changed in the past. The U.S. has the best and longest meteorological records and they should be examined and displayed in their entirety. Trend analyses should include longest periods available and employ suitable statistical methods. Local paleoclimate data should be considered where available. Analysis should demonstrate not only how the climate has varied and changed, but also regional heterogeneity. Standard, easily understandable metrics should be employed.
- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future. The regional chapter for REGION that includes Texas only stated that
- A critical survey of current global and regional modeling capabilities and their suitability for regional impact assessments and projections. This would include an assessment of their ability to reproduce observed changes. It should also discuss alternative methods for generating projections and forecasts on regional and decadal scales, along the lines of Chapter 10 of the IPCC AR6 WGI Report.
- Assessment of the impacts of recent historical climate variability and change on ecosystems and society. Where long-term data indicate a detectable regional change, regional projections can be made for the period 2030-2050. Emissions scenarios exceeding RCP4.5/SSP2-4.5 and ECS values exceeding 4°C should not be used. Regional projections to 2100 have no credibility at this time.

It is important that climate projections be assessed in context of current science capabilities. The pressures toward spatially or temporally precise projections should be resisted as the current models are nowhere up to the task (an example is discussed in CWG25 Section 5.8). In that light, the many pages of NCA5 devoted to projected regional and sectoral impacts have little value.

Given the substantial deficiencies and bias in NCA5 that we have identified, producing an objective NCA6 report with the current NCA organizational construct would be a challenge. A NASEM review could help, but only if the selected participants reflect full viewpoint diversity and do not simply mirror the assumptions and biases of past NCA teams. We regard the CWG25 report to be a good start on NCA6 in terms of scope and objectivity, including adherence to the tenets of Gold Standard Science.

More broadly, we recommend a rewrite of the Global Change Research Act. The current mandate is vague and off point, allowing successive NCA teams to interpret the mandate as they see fit. Moreover, it is becoming increasingly clear that current and foreseeable models are not fit-for-purpose to describe regional climates, let alone usefully project them for 25 and 100 years. Further, the use of the term “global change” is ambiguous and outdated.

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APPENDICES

APPENDIX 1: Charge to the review

ABOUT THE AUTHORS

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Review of the Fifth National Climate Assessment

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EXECUTIVE SUMMARY

This report critically evaluates the Fifth National Climate Assessment (NCA5), finding it an inadequate basis for climate and energy policies. A detailed review of the foundational chapters on climate science raises several key concerns:

Scientific Integrity

- An advocacy tone, particularly in the Overview chapter, inconsistent with scientific objectivity
- An endemic overconfidence when stating conclusions, including inflated certainty levels and overstatement of findings from underlying sources

Flawed methodology

- Use of *ad hoc* time scales for trend analyses in areas such as precipitation and heatwaves
- An overemphasis on extreme scenarios for future emissions
- Inadequate traceable accounts to support key conclusions

Deficient Review Process

- A review by the National Academy of Sciences, Engineering, and Medicine (NASEM) failed to challenge some fundamental flaws in NCA5
- The NCA5 authors failed to adopt some improvements recommended by NASEM

The report shows NCA5 to be a biased and incomplete picture of climate science that skews toward excessive climate risk. Consequently, NCA5 should not be used as basis for climate and energy policies.

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1 INTRODUCTION

1.1 About this Report

This report responds to a request from OSTP Director Michael Kratsios (reproduced in Appendix XX1) that we assess the suitability of the [HYPERLINK "<https://nca2023.globalchange.gov/>"] for informing climate and energy policies.

To conduct this assessment we reviewed NCA5 itself, ~~the NASEM–National Academies (NASEM)~~ review of the Third Order Draft, and the USGCRP responses to ~~the~~ that review. We have drawn upon our long experience working on advisory reports, including for the NASEM, ~~the~~ IPCC and other organizations, as writers, reviewers and ~~project~~ study leaders.

~~We find that NCA5 should not be relied on for policy making as it is an incomplete and misleading picture of our understanding of the changing climate and the risks it poses to the nation. NCA5 was selective and incomplete in its survey of the climate science as of its publication date in 2023 and has become even more so in the years since. We have reviewed many key scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025, herein denoted "CWG25"). The overall effect of the biases and omissions of NCA5 is an excessively dire picture of climate risk.~~

~~Our report begins with~~To support our finding, the following sections of this chapter provide some background on the National Climate Assessments and the standards by which we have assessed NCA5. Chapters 2 through 6 ~~then~~ detail important ways in which NCA5 fails to meet those standards. In Chapter 7, ~~then~~ follows with an assessment of the NASEM review. Finally, Chapter 8 summarizes our evaluation of NCA5. We then discuss the standards by which we have assessed NCA5, followed by specific deficiencies that we have identified

~~We find that NCA5 should not be relied on for policy making as it is an incomplete and misleading picture of our understanding of the changing climate and the risks it poses to the nation. NCA5 was selective and incomplete in its survey of the science as of its publication date in 2023 and has become even more so in the years since. We have reviewed many key scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025, herein denoted "CWG25"). The overall effect of the biases and omissions of NCA5 is an excessively dire picture of climate risk.~~

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1.2 About the National Climate Assessments

The [HYPERLINK "<https://www.globalchange.gov/>"] (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The National Climate Assessment (NCA) Reports evolved from the GCRA requirement to

Prepare and submit to the President and the Congress an assessment which (1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyzes

current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

The five NCA Reports to date have interpreted this mandate in different ways:

- NCA1 (2000) was a multidisciplinary effort to study and portray in regional detail the potential effects of human-induced global warming on the United States.
- NCA2 (2009) was a relatively short report that not only focused on the potential consequences of climate change, but change but also sought to identify potential adaptation measures and identify the highest priorities for future research.
- NCA3 (2014) was an expanded effort that continued along the lines of NCA2, and was distinguished by a comprehensive review process, including a review by the National Academy of Sciences. NCA3 introduced a traceability analysis for each key finding, including a description of uncertainties.
- NCA4 (2017/2018) was an further expanded effort published in two volumes: I Climate Science Special Report, and II Impacts, Risk, and Adaptation in the United States. This was the first NCA report to devote significant effort to assessing climate science.
- NCA5 (2023) returned to a single volume format, reducing discussion of climate science to a cursory two chapters, with continuing with a focus on regional and sectoral impacts of climate change. NCA5 expanded its remit to topics that are arguably outside the purview of the USGCRP, focusing on "Climate Action" and policy recommendations with a social justice emphasis. NCA5's self-description is reproduced as Appendix II.

These successive interpretations of the NCA are poorly aligned with the GCRA's statutory requirements. Only NCA4 gives serious consideration to climate science, which receives the great majority of USGCRP funding, and even then misrepresents some important points (Section 1.4 below offers an example). Natural climate variability is essentially dismissed as unimportant in NCA4 and barely mentioned in NCA5 in most contexts, despite the mandate to include both human-caused and natural climate change. Most significantly, NCA5 has redirected the focus away from climate science and even the hazard elements of impacts, towards evaluation of societal vulnerabilities and advocacy for particular policy options, especially wind and solar power. The cover image for the NCA5 Report is the installation of a solar panel.

1.3 Standards for Assessing NCA Products

In Appendix ~~2XX~~ we include a letter of guidance from the Office of General Counsel, U.S. Department of Energy, summarizing the ~~extent of~~ statutory requirements governing USGCRP work products in general and NCA products in particular.

We can summarize the standards applicable to the NCA as follows:
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Beyond the statutory requirements we draw attention to two other pertinent standards. President Trump's executive order of May 23, 2025, "[[HYPERLINK "https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/"](https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/)]" enumerates some of the characteristics of good science:

- i. reproducible;
- ii. transparent;

- iii. communicative of error and uncertainty;
- iv. collaborative and interdisciplinary;
- v. skeptical of its findings and assumptions;
- vi. structured for falsifiability of hypotheses;
- vii. subject to unbiased peer review;
- viii. accepting of negative results as positive outcomes; and
- ix. without conflicts of interest.

Although these should be self-evident to those trained in science, it is surprising that some ~~scientists~~ have found them [[HYPERLINK "https://www.theguardian.com/commentisfree/2025/may/29/trump-american-science"](https://www.theguardian.com/commentisfree/2025/may/29/trump-american-science)].

~~There are other desiderata for scientific reports. When scientific reports are being assembled that will be highly influential on climate policymaking, there are other desiderata, including~~ Among them are statements about the strength of climate knowledge. The IPCC's approach is based on judgment of the available evidence and agreement among experts. More sophisticated knowledge characterizations for risk management include (Aven 2017)¹:

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
- The degree to which data/information exists and are reliable and relevant
- The degree to which there is disagreement among experts (including those from different environments or academic fields)
- The degree to which the phenomena involved are understood and accurate models exist
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns

Good climate and energy policies will balance the risks and benefits of a changing climate against the world's growing demand for reliable and affordable energy. To strike that balance, policymakers must understand at least two complex and nuanced topics: the certainties and uncertainties of climate science and the technoeconomic realities of energy systems. Experts in those subjects have a ~~unique~~ responsibility to communicate their understanding to non-experts clearly, completely, and without bias.

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Expertise in energy systems resides largely in the private sector, where it is essential to providing the reliable and affordable energy services that are the lifeblood of society. Understanding is therefore continually refined and tested by the discipline of the marketplace. In contrast, climate science expertise is found largely in the non-profit realm of universities and government laboratories and so has a more academic character.

In recent decades, climate science has engendered passion and emotion. Indeed, some younger climate scientists have gone into the field to "save the planet." ~~Further, the field of climate science has been politicized by NetZero mandates. So it is it is then~~ not surprising that objectivity can suffer when climate scientists communicate their understanding to non-experts. ~~Further, the field of~~

¹ Aven, Terje (2017) "Improving Risk Characterisations in Practical Situations by Highlighting Knowledge Aspects, with Applications to Risk Matrices," *Reliability Engineering & System Safety* 167 (November 2017):42-48 [[HYPERLINK "https://www.sciencedirect.com/science/article/pii/S0951832016306950"](https://www.sciencedirect.com/science/article/pii/S0951832016306950)]

climate science has been politicized by NetZero mandates. This lack of objectivity usurps the public's right to make informed choices and undermines their confidence in the scientific enterprise.

In 1980, then-President of the National Academy of Sciences Philip Handler identified the problem in an editorial² that resonates eerily four decades later:

Difficulty arises in the scientific community from confusion of the role of scientist *qua* scientist with that of scientist as citizen, confusion of the ethical code of the scientist with the obligation of the citizen, blurring the distinction between intrinsically scientific and intrinsically political questions. When scientists fail to recognize these boundaries, their own ideological beliefs, usually unspoken, easily becloud seemingly scientific debate.

1.4 When Peer Review Fails

Peer review of reports like IPCC and NCA products is not a silver bullet that guarantees quality. The peer review process for these reports differs in some important respects from traditional peer review in academic journals. First, NCA reviewers are volunteers who self-select on a volunteer basis whether to provide comments and what parts of the report to read, whereas the editors of academic journals recruit reviewers and assign them to specific papers. As a result, there is no guarantee that any particular section of an NCA report was reviewed by anyone, WHAT ABOUT THE NASEM REVIEW? let alone by someone with a perspective that differs from the authors. This is a problem with NCA and IPCC reports since, in fact, over the years many potential reviewers have given up over the years making the effort, because their input has systematically been ignored. Second, NCA authors have near complete authority whether to accept or reject review comments. Here, for example, is how a review comment critical of a section of the NCA5 draft was handled by the authors:

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By contrast, in academic journals the Editor of an academic journal mandates the author to respond and the reviewer and editor gets to assess its adequacy. And third, the work of an NCA chapter author team is guaranteed to be published, whereas academic journals routinely reject papers that do not pass review.

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Once an NCA chapter author team has been selected publication of their work is guaranteed, whereas academic journals routinely reject papers if they do not pass review.

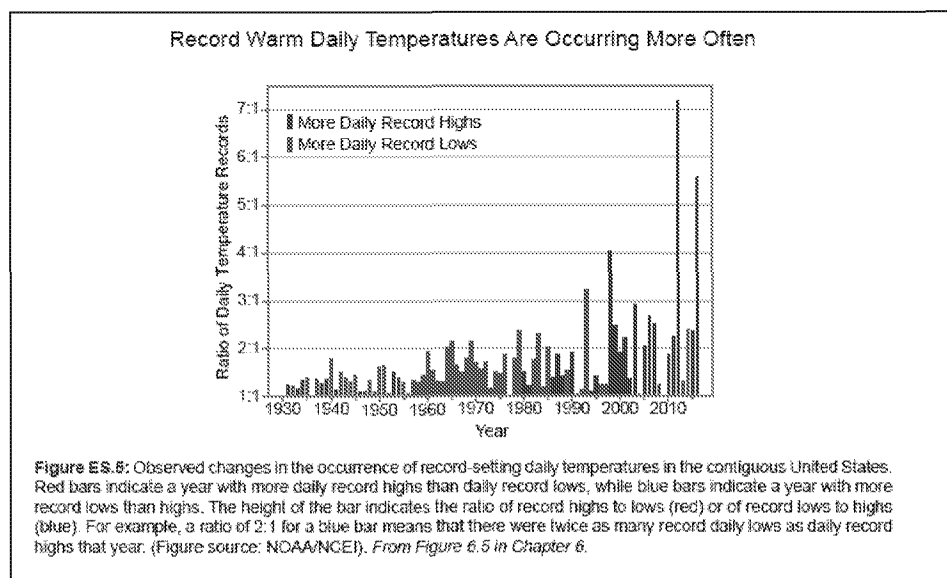
These points are important to bear in mind because some readers might dismiss any criticism of NCA products out of hand on the grounds that they were "peer reviewed". But the test of a report is whether its contents are a valid representation of the available evidence. Here we give an example in which NCA4 gave prominence to a Figure that completely misrepresented the underlying data and which evaded peer review to do so. Further details can be found in Koonin (2024).

As we pointed out shown in CWG25 Section 6.3 the number of heat extremes in the U.S. peaked in the 1930s and has declined ever since. Considering cold and hot extremes together the U.S. climate has become more moderate over time. NCA4's Part I ([[HYPERLINK "https://science2017.globalchange.gov/"](https://science2017.globalchange.gov/)], CCSR) says (prominently and with *Very High Confidence*) on Page 19 of the Executive Summary:

² Handler, Philip (1980) Public Doubts About Science. *Science* 208(4448) p. 1093 [[HYPERLINK "https://www.science.org/doi/10.1126/science.208.4448.1093"](https://www.science.org/doi/10.1126/science.208.4448.1093)]

There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records.

and offers this figure in support:



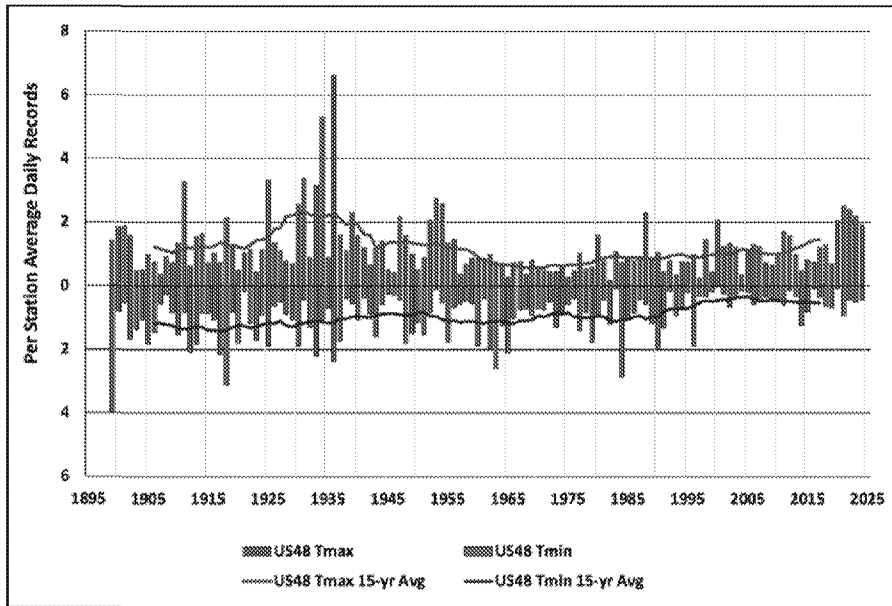
The figure appears to validate the claim that record warm daily temperatures are occurring more often. But the underlying data do not. Rather, they show that extreme heat in the U.S. peaked in the 1920s and 1930s and declined thereafter, as supported by NCA4—Figure 6.4 itself later shows deep within the CSSR itself (reproduced in our Section 4.2 below).

Figure ES.5 does not even show what its title implies, as it displays these are not simple counts of cold and warm extreme events, but rather, instead they are ratios of the two counts. In fact, both types of extremes declined over the sample interval, but cold events declined more than warm events, so the ratio of warm extremes to cold extremes increased. By graphing the ratio in this way instead of counts, the NCA4/NCA4 creates a visual impression opposite to what is in the data.

Figure 6.3.3 of CWG25 (reproduced below) shows the results of a proper analysis of the data – defining each record as the singular extreme in the history sample interval, displaying numbers of warm and cold records separately, and beginning the analysis in 1899 rather than 1930. It makes evident the exceptional heat of the 1920s and especially the 1930s, peaking in 1936.³ The increased heat of the past five years is too brief to be deemed climatically significant and, in any event, occurred

³ The increased heat of the past five years is too brief to be deemed climatically significant and, in any event, occurred after the CSSR was published in 2017.

after the CSSR was published in 2017. The frequency of cold records has declined, especially over the last quarter of the period in which only 13 percent of the extreme cold events were measured. In contrast, 25 percent of the extreme Tmax-heat records were achieved in the last quarter, which is consistent with statistical expectations. As a result, the ratio of heat to cold extremes shown in Figure ES.5 of the CSSR explodes in recent decades. The overall reduction in numbers of both cold and hot extremes over the past century indicates a climate *less* prone to extremes, in sharp contrast to the message of the NCA4 Figure ES.5.



Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92 percent of observations in the 126-year period since Dec 1898. US48: contiguous U.S. states. Tmax: maximum temperature. Tmin: minimum temperature. Source: CWG25 Figure 6.3.3.

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The National Academies' expert review panel [[HYPERLINK "https://www.nap.edu/catalog/24712/review-of-the-draft-climate-science-special-report"](https://www.nap.edu/catalog/24712/review-of-the-draft-climate-science-special-report)] the discussion of temperature extremes in a [[HYPERLINK "https://biotech.law.lsu.edu/blog/Draft-of-the-Climate-Science-Special-Report.pdf"](https://biotech.law.lsu.edu/blog/Draft-of-the-Climate-Science-Special-Report.pdf)] of the CSSR. In reference to the CSSR's Key Finding 2 of Chapter 6, they said:

Further, it is difficult to understand how a statement that includes increases in extreme warmth can be associated with a high confidence or extremely likely

statement, given that most of the graphics in this chapter show a decrease in extreme warmth in the historical record.

The Federal official in charge of the CSSR (Michael Kuperberg, Executive Director of the USGCRP) [[HYPERLINK "https://science2017.globalchange.gov/PDFs/CSSR-NASresponse_110217.pdf"](https://science2017.globalchange.gov/PDFs/CSSR-NASresponse_110217.pdf)] to the Academies' review by noting that

Almost every recommendation from the NAS was incorporated [in the final version]... and a new figure was added on changes in record high and low temperatures

The "new figure" referred to is the Figure ES.5, which did not appear in the draft reviewed by the Academies' panel. It seems unlikely that the Academies panel ever saw that figure because they surely would have commented if they had and it wouldn't have survived to publication. And the figure's problems were evidently not flagged (or were ignored) in the subsequent internal government reviews.

With this background we now present our critique of NCA5.

2 NCA5 OVERVIEW CHAPTER: HYPERBOLIC ADVOCACY LANGUAGE AND

non-UNSCIENTIFIC TONE

2 [Fix formatting in "UNSCIENTIFIC"]

NCA5 Chapter 1, "Overview", holds a prominent place in the Report since it summarizes the ~~entire~~ whole report and is the only section that many will read. Although the later ~~c~~Chapters of NCA5 contain much sound scholarly content, Chapter 1 is marred by an activist tone and language that aggressively promotes ~~emission reduction~~mitigation policies. As such, this chapter adds an imprimatur of scientific authority to oversimplified declarations of opinion about public policy. Many examples can be cited; here we note a few that are particularly egregious.

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Chapter 1 opens as follows:

The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases.

This statement presupposes that: all warming is anthropogenic in origin, that all warming is bad and causes economic ~~damage, damage, and that~~ warming causes ~~intensifies~~ extreme weather to intensify. Such sweeping generalizations go well beyond what science has or can establish. ~~It~~ The statement also refers to growing risks without saying whether they were large to begin with -- a small risk that grows may still be a small risk, and a large risk may be only incrementally worsened. A scientifically-sound version of this paragraph would instead say something like the following:

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The Earth is warming because of a combination of natural and anthropogenic influences. This warming will generate a mix of benefits and harms that varies by region, to which society should be prepared to adapt. Some types of extreme weather have worsened recently, while others have not changed or have even declined in intensity. Reducing emissions of greenhouse gases might slow the warming although such policies have proven to be costly and disruptive, so any climate actions to be weighed against the potential benefits.

On the next page the Overview ~~states goes on to say:~~

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Each additional increment of warming leads to greater risks [here it lists 7 key components of society including food security and the economy]... Without deeper cuts in global net emissions, climate risks to the US will continue to grow... Action to limit future warming and reduce risks can have near-term benefits and opportunities: low-carbon energy jobs, Improved air quality, Health benefits, Economic benefits..."

The authors write as if climate policy does not involve trade-offs and all measures to reduce future warming will be effective and beneficial. But the vast body of scholarship on climate science and economics does not support such simplistic claims. Not every additional increment of warming leads

to economic harms; in fact, indeed (as is acknowledged in NCA5 Chapter 19 acknowledges that on Economics) in some cases there will also be benefits. Nor is climate policy guaranteed to create jobs or benefit the economy; in many cases it has done the opposite. Such deceit is a disservice to policymakers.

Pages 8 and 9 of the Overview promote renewable energy options by noting, correctly, that the leveled costs of wind/solar generation have fallen sharply since 2010, and so offers. This is proposed this as rationale for pursuing deep emission reductions:

Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources.

Yet it has long been known that intermittent renewables generation must be supplemented by dispatchable generation to meet grid reliability standards, and that doing so (e.g., through natural gas, fission, or storage) can substantially increase significantly increases the cost of electricity. Further, there are yet unmet synchronization challenges in transmission grids with heavy penetration of wind and solar power. Here again it is advisory malpractice not to acknowledge these facts.

Page 14 of the Overview presents future emission scenarios with the following description: "Climate modeling experts develop global climate projections for a range of plausible futures." The word "plausible" is applied to all of the scenarios. The accompanying Figure includes both SSP3-7.0 and SSP5-8.5, the latter reaching the same radiative forcing as RCP8.5. The Figure does not contrast compare observed emissions against with previous projections nor does it caution readers that SSP3-7.0 and SSP5-8.5 are extreme worst cases scenarios that, like RCP8.5, have been heavily criticized in the scientific literature (CWG25 3.2.1). By describing the entire envelope of emission projections as "plausible" the report opens the door to later presenting impacts associated with extreme and implausible emission scenarios as part of a baseline "business-as-usual" future.

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Page 17 of the Overview introduces the discussion of risks from extreme weather events by saying "Harmful impacts from more frequent and severe extremes are increasing across the country." This creates the impression that disaster losses are driven by trends in extreme weather. While the section goes on to acknowledge that some of the increase is due to increases in the value of assets at risk it then invokes the NOAA Billion Dollar Dataset as evidence of extreme weather getting worse. Scientists have shown that this is an invalid metric (CWG 10.2) since it measures the growth of the economy not the frequency of extreme weather, and indeed NOAA has recently withdrawn the data product REFERENCE PIELKE JR PAPER. Even though it was still distributed by NOAA at the time of the NCA5, the report authors should have assessed it skeptically and seen that it was unfit for the purpose of measuring climate trends and they should have taken care not to conflate extreme weather metrics with economic trends.

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Page 23 of the Overview states, in large font:

Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities.

It is pointless to try to evaluate this statement on scholarly grounds; it is self-evidently hyperbolic. This kind of language doesn't belong in a scientific assessment report. Its prominent inclusion points not only to the willingness of NCA5 authors to promote hysterical alarm, but also the ineffectiveness of the review process ~~in~~ not ensuring such statements are removed.

The tone of the Overview chapter hints at the priorities that governed the writing of the ~~entire~~ report as a whole. ~~Word counts of the full report are another~~ As a crude indicator of these priorities, word searches of the full document revealed the following occurrences:

Term	Number of occurrences
Forcing	111
Uncertainty	384
Watts	19
Culture/culturally	854
Equity/equitable	572
Indigenous	890
Sustainable	295
Racism/racial	153

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS

3.1 Inflated certainty levels
~~Overconfidence in stating conclusions is an endemic problem in NCA5. A general pattern in the NCA5 is overconfidence in stating conclusions.~~ The authors frequently make sweeping generalizations without appropriate caveats or acknowledging uncertainties. The overconfidence begins with inflated language to describe certainty levels.

The NCA5 uses specific terms to convey information about scientific confidence associated with important finds, observations and projections. The Front Matter of the NCA5 states that

“confidence in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.”

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and Table 1 from the Front Matter provides calibrated language for confidence assessment:

- Very high: Strong evidence (established theory, multiple sources, well documented and accepted methods, etc.). High consensus
- High: Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.). Medium consensus
- Medium: Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) Competing schools of thought.

Low: Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.). Disagreement or lack of opinions among experts.

This terminology is inflated: *high confidence* with just moderate evidence and medium consensus; *medium confidence* with only suggestive evidence and competing schools of thought. This inflation in terminology leads to overconfidence in the ~~conclusions~~ conclusions.

Even within the context of this with this inflated terminology, NCA5 further inflates the confidence level of many of its conclusions to well beyond what the IPCC has concluded with more thorough justification, and also by incorrectly applying its own standards. Several illustrative examples are provided. Here are two examples.

Key Message 3.1 Traceable Account states:

"There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused *all* global warming observed over the industrial era."

Compare this statement with statements while the corresponding statements from the IPCC AR5 and AR6 are:

AR5: "It is *extremely likely* that *more than half* of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together." (IPCC, 2013)

AR6: The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.

The IPCC AR5 and AR6 statements provide likelihood assessments but not a confidence level. While the NCA5 claims with *very high confidence* that fossil fuels have unequivocally caused *all* global warming, the AR5 refers to "*more than half* of the observed warming" and the AR6 provides a more nuanced statement that relates to a *likely* range of warming contributed to by human drivers.

As a second example, NCA5 Key message 2.2 reads:

"Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*)."

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No justification is provided in Chapter 2 for the *high confidence* conclusion on higher storm surges or hurricanes causing heavier precipitation. The Traceable Accounts section, Description of Confidence and Likelihood states:

Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the

authors also have *high confidence* that storms are delivering more rainfall and high confidence that storm surges are becoming higher.

In short, NCA5 provides no observational basis or published research for their *high confidence* assertions that hurricanes are causing heavier rainfall and higher storm surges, thus failing to; and does not meet its own standards for a *high confidence level*.
THIS EXAMPLE IS USED IN TRACEABLE ACCOUNTS

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3.2 Overstating findings in underlying sources

Although we did not do a detailed audit of the NCA5's use of source material, spot checks turned up evidence of a pattern of overstatement.

Chapter 2 page 11 reports on an increase in precipitation in some areas and attributes it to human caused climate change:

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Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.⁵

Note that this a non-standard metric; we will discuss NCA5's inconsistent choices of time scales of analysis below. The claims were attributed to the following paper:

- Knutson, Thomas and Fanrong Zeng (2018) "Model Assessment of Observed Precipitation Trends over Land Regions: Detectable Human Influences and Possible Low Bias in Model Trends" *Journal of Climate* 31(12) [[HYPERLINK "https://journals.ametsoc.org/view/journals/clim/31/12/jcli-d-17-0672.1.xml"](https://journals.ametsoc.org/view/journals/clim/31/12/jcli-d-17-0672.1.xml)]

But Knutson and Zeng did not say these things. They examined linear trends over 1901 – 2010, 1951 – 2010 and 1981 – 2010. They did not compare average rainfall over 2002 - 2021 to average rainfall over 1901 – 1960, indeed if only because their study was published in 2018 so it could not have. With regard to For 1981-2010, trends they noted stronger trends in some areas but cautioned that such changes are consistent with natural variability, and they did not claim attributable trends were observed over the United States:

Observed annual precipitation trends over the recent 30-yr period 1981–2010 ([[HYPERLINK "https://journals.ametsoc.org/view/journals/clim/31/12/jcli-d-17-0672.1.xml"](https://journals.ametsoc.org/view/journals/clim/31/12/jcli-d-17-0672.1.xml)] \ "fig5"]) have generally stronger magnitudes (in mm yr⁻¹ decade⁻¹) than observed trends for 1901–2010 or 1951–2010. This is as expected since trends over a shorter period have stronger potential for occurrence of pronounced temporary trends due to internal variability alone. Only 9% of the analyzed area has detectable and attributable anthropogenic influence (categories -3, -2, +2, +3), which represents less than one-third of the fractional areal coverage of such trends for 1901–2010 (29%). ... Eight percent of the analyzed area has attributable anthropogenic *increases* (categories +2, +3), including parts of eastern Europe, northern Asia, northern Australia/Maritime Continent, and tropical Africa.

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⁵ Quite separately we note that the attribution to "climate change" is misleadingly ambiguous. Because NCA5's Glossary defines "climate change" as a change in climate for any reason, the statement is a tautology and so the attribution is superfluous. But because the popular perception of climate change is anthropogenic, its gratuitous inclusion effectively attributes the changes to greenhouse gas emissions. [FIX FORMATTING HERE]

As another example of overstating findings, Consider a 2nd example. NCA5's Chapter 2 page 18 states

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.

This is allegedly attributed to two papers:

- Diffenbaugh, N.S., D. Singh, and J.S. Mankin, 2018: Unprecedented climate events: Historical changes, aspirational targets, and national commitments. *Science Advances*, **4** (2), 3354. [HYPERLINK "<https://doi.org/10.1126/sciadv.aao3354>"]
- Kirchmeier-Young, M.C. and X. Zhang, 2020: Human influence has intensified extreme precipitation in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13308-13313. [HYPERLINK "<https://doi.org/10.1073/pnas.1921628117>"]

Diffenbaugh *et al.* presented ratios of observed occurrences of extreme events to simulated occurrence rates in CMIP6 models run with only natural forcings. They report that for 79% of the U.S. extreme rainfall event frequencies are currently higher than in model simulations, and the ratio of occurrences will rise under future warming simulations. This is not "robust" evidence of anthropogenic influence since it requires readers to assume that climate models provide accurate simulations of regional precipitation patterns, something which that even the IPCC AR6 admits is uncertain (AR6 WGI SPM Box SPM 1.2, SPM Section C.1.3).

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Kirchmeier-Young and Zhang looked at extreme 1- and 5-day events in North America and, using three GCMs, found

"A signal of combined anthropogenic and natural external forcing can be detected in the intensification of extreme precipitation at the continental scale over North America. In some cases, this intensification can be attributed to human influence specifically."

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However, they noted large differences among the three models in their simulated precipitation changes. Also, two of the three models failed to yield attribution for 5-day events for the North America mean, in other words the models disagreed on whether the observed changes were due to anthropogenic activity. Both cited references utilized the implausible RCP8.5 scenario and began their "historical" observational records only in 1961. Here again this is not "robust" evidence, it is merely suggestive, particularly since but other studies have found natural variability predominant.

3.3 Technical example: Emergent constraints

Some of the overconfidence expressed by NCA5 arises by leaving out omitting discussion of counterevidence in the peer-reviewed literature. An example is the topic of "emergent constraints". Chapter 3 page 17 invokes this concept as grounds for to support its claim that key uncertainties have been reduced:

An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as "emergent constraints." The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship.

Emergent constraints appeared in the climate modeling literature as an attempt to tie GCM behavior to climate observations in hopes of generating insight into real-world ~~ECS, equilibrium climate sensitivity to a doubling of carbon dioxide (ECS)~~. Climate models exhibit a wide range of ~~sensitivities~~ ECS values. The idea of emergent constraints is to examine whether the models with shared sensitivity values also share a common representation of some climate process (usually related to clouds) that might indirectly influence ECS. Suppose, for instance, that in low-ECS models the total cloud fraction in the tropics is strongly correlated with that in the southern midlatitudes but in high-ECS models the correlation is weak. Then researchers could ~~examine whether~~ check if the observed correlation is strong or weak and draw a conclusion about which type of model, and therefore which ECS value, is more likely.

A problem in the emergent constraint literature is that there has been a large proliferation of proposed correlations with little physical motivation. Many emergent constraints patterned on CMIP5 models failed to work on CMIP6 models (Schlund *et al.* 2020)⁵. In other words, the observed correlations in CMIP5 models between ECS and cloud processes failed to show up in CMIP6 models, indicating that they were likely spurious rather than clues to physical processes governing the Earth climate system. The result was that emergent constraints estimated ~~on~~ from CMIP5 models ~~widened~~ the range of estimated ECS values when applied to CMIP6 models.

Schlund *et al.* summarized the problem as follows ~~[boldface used for emphasis]~~:

In this study, we systematically analyze 11 published emergent constraints on ECS that have mostly been derived from models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) project... The focus of the study is on testing if these emergent constraints hold for [Earth System Models] participating in the new Phase 6 (CMIP6). Since none of the emergent constraints considered here have been derived using the CMIP6 ensemble, CMIP6 can be used for cross-checking of the emergent constraints on a new model ensemble. **The application of the emergent constraints to CMIP6 data shows a decrease in skill and statistical significance of the emergent relationship for nearly all constraints, with this decrease being large in many cases.** Consequently, the size of the constrained ECS ranges (66% confidence intervals) widens by 51% on average in CMIP6 compared to CMIP5.

Yet NCA5 described the use of emergent constraint analysis as a great "advance" that reduced uncertainty.

⁵Schlund, Manuel, Axel Lauer, Pierre Gentile, Steven C. Sherwood, and Veronika Eyring (2020) Emergent constraints on equilibrium climate sensitivity in CMIP5: do they hold for CMIP6? *Earth System Dynamics* 11 1233-1258 [HYPERLINK "<https://doi.org/10.5194/esd-11-1233-2020>"] ~~[Need to be consistent on where references go]~~

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4 RELIANCE ON *Ad Hoc* TIME SCALES FOR TREND ANALYSIS

In CWG25 Chapter 6 we discussed the need to be careful regarding care in the choice of time scale when making claims about trends in extreme weather. We gave provided examples from analysis of river flooding (6.1), heatwaves (6.3), and extreme precipitation (6.4) to show how assertions about apparent trends based on short data sets fall apart when looking at longer versions of the same data sets. Here we elaborate on these examples to illustrate the general point that NCA5 made inconsistent and *ad hoc* choices about time scales of analysis, weakening the validity of their conclusions.

McKittrick and Christy (2019)⁶ CWG25 Section 6.4 showed that apparently significant positive trends in U.S. average and extreme precipitation over the NCA4 interval (1901 – 2016) disappeared on longer samples (extending back as far as the 1840s, depending on location) or on a shorter interval coinciding with the final 40 years of the data then available (1978 – 2017).

In CWG Section 6.4 we presented analysis of updated data for the same locations (and many more others) besides, in all cases finding both considerable regional heterogeneity and that trends detectable on one time scale are often not detected on longer or shorter time scales. These findings, which argues against simple attribution of changes to anthropogenic influences.

4.1 Average and Extreme Precipitation

Under Key Message 2.2 “Extreme Events Are Becoming More Frequent and Severe” (p. 2-16) NCA5 states (p. 2-18):

Rainfall is becoming more extreme
Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US. This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity.

NCA5 did not continue the NCA4 precedent of using the post-1901 interval as the time scale for its precipitation discussion; instead it refers to changes “since the 1950s”. NCA5 Figure 2.8 suggests 1958 as the start date. For the present report we have extended the CWG25 analysis even further to include 141 stations across the US in the Pacific Coast, Midwest, Northeast and Southeast regions. We provide details in Appendix B3; here we note merely that once again it is possible to find trends that support the NCA5 position, but they are not robust to selecting longer or shorter time scales of analysis. Data from 1950 to 2024 yields many indications of increased average and extreme precipitation at individual stations and region-wide averages. But when using the entire data set (back to the 1890s or earlier, depending on location) or the later subset (1980 to 2024) the trends become smaller, in many cases they become statistically insignificant, and occasionally they even change sign. Only in the Northeast region are the post-1950 trends robust to also focusing on trends during the post-1980 interval.

The following is a more accurate summary of what U.S. data show.

⁶ McKittrick, R., and J.R. Christy (2019). Assessing changes in US regional precipitation on multiple time scales. Journal of Hydrology, 578, 124074. [HYPERLINK “https://doi.org/10.1016/j.jhydrol.2019.124074”]

There are regionally-heterogenous changes in average and extreme precipitation. Positive trends in annual average rainfall and extreme events (defined either as the annual maximum or the number of exceedances of the 99th percentile value) are generally weak or non-existent when looking at samples exceeding 130 years in length. Significant trends can be found when beginning the sample in the 1950s although in most cases the trends weaken and become insignificant when looking at the post-1980 interval. This makes attribution of changes in precipitation to anthropogenic warming difficult.

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4.2 Heatwaves

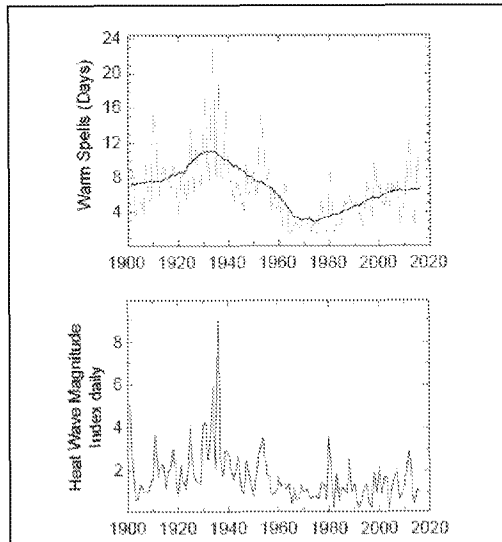
In contrast to NCA5, NCA4 examined heat extremes across the whole of the entire 20th century, pointing out that peak heat wave activity was reached in the 1930s and has decreased since then, and that recent increases are confined to areas west of the Rockies:

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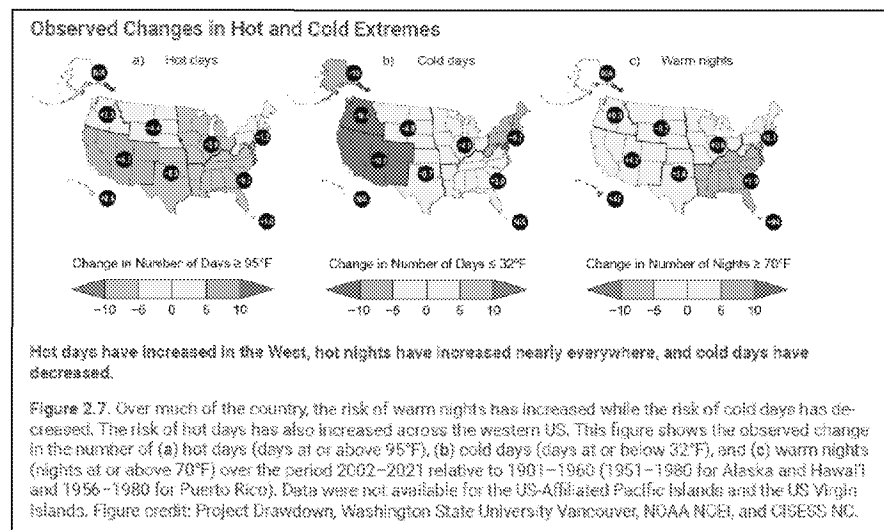
[The] warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]).

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.
(NCA4 pp. 190-191)



U.S. Heat waves since 1900. Source: NCA4 Figure 6.4

Contrast this careful and factual language with NCA5 Key Message 2.2: "Extreme Events Are Becoming More Frequent and Severe." This blanket statement is followed by NCA5 Figure 2.7 (reproduced below) which shows the number of hot days, cold days and warm nights (respectively in panels a—c) over the period 2002-2021 compared to 1901-1960. [Presumably these are annual counts, although not stated in the caption.]



Close inspection shows that this figure contradicts the NCA5 Key Message with respect to heatwaves and instead reinforces the position of the NCA4. The time scale of analysis for this figure is stated as the number of hot days, cold days and warm nights (respectively in panels a–c) over the period 2002–2021 compared to 1901–1960. Presumably (though not stated in the caption) the counts are per year. Notwithstanding Key Message 2.2 the leftmost panel in Figure 2.7 above shows that over most of CONUS the number of extreme heat days has decreased in recent decades compared to the prior century.

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The accompanying discussion in NCA5 becomes convoluted since as it appears to be aimed at supporting the Key Message despite the contrary evidence. NCA5 chapter 2 elaborates on Key Message 2.2 by saying (page 16):

Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*).

But it does not fail to mention WHAT DECLINE the decline elsewhere. Instead, it says -o On the next page (page 17) it says: THIS POINT IS UNCLEAR

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By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s. ... Globally such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends.

The reference to a global trend seems to be an attempt to tie heatwaves to climate change. But, but then the obvious question, unaddressed by NCA5, is why it WHAT?? holds for only part of the U.S. follows it while most of the country is trending in the opposite direction. These issues were addressed in Chapter 6 of CWG25_Ch6, demonstrating that the range and magnitude of extreme

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temperatures (10s of degrees) are driven more by natural variability than by the small anthropogenic extra forcing from the enhanced concentrations of CO₂. The data shown analysis in CWG25 shows that in terms of for both (a) hot days ($\geq 95^\circ\text{F}$) and (b) number of days in heatwaves, the current decade is experiencing no more than was experienced no hotter than a century ago. 100 years ago. For example, in during the 30-year period 1925-1954, (representing only 23% of the 1899-2024 data record), the CONUS experienced 33% of the total heat wave days and during the most recent 30-years it experienced 24%, almost exactly that expected by chance. Thus, the NCA5 claim that "multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades," is seen to be simply false when expanding the temporal and spatial domains to encompass all available data (Chapter 6 and Figure 6.3.6 of CWG25).

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The NCA5 then pointed to the dramatic Pacific Northwest heatwave of 2021. CWG2025 Section 8.6.1 discussed this event in detail, reviewing the findings of multiple peer-reviewed studies that explained the unusual meteorological conditions context giving rise to it were was unrelated to human caused climate change, a point omitted from the NCA5 discussion.

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NCA5 finally turns to addresses the declining heatwave trend in CONUS east of the Rockies but attempts to reframe it by focusing on urban warm spells.

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[The] number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades. Across 50 large US cities, the US Global Change Research Program heatwave indicator ([HYPERLINK "https://www"] [globalchange.gov/indicators/heat-waves](https://www.globalchange.gov/indicators/heat-waves)) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.

We discussed this issue WHAT ISSUE in CWG25 Section 6.3. The Figure referenced by NCA5 uses an *ad hoc* definition of heat wave, namely two consecutive days with minimum nighttime temperatures above the 85th percentile, and an *ad hoc* time scale which begins in the 1960s, the coldest decade in the last century, thus suppressing any comparison to the 1930s. Further, nighttime temperatures in urban areas have gone up increased faster than daytime temperatures (which the NCA5 acknowledges), but this is a signature of urban heat islands effects and is and not a good metric of climate change. CWG25 noted as well that the occurrence of hot days ($\geq 95^\circ\text{F}$) has recently increased in the West, but declined in the remainder of the country, and in the nationwide average, since 1899.

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5 INADEQUATE TRACEABLE ACCOUNTS

Starting with the NCA3 began the practice of including, the NCA has included a section on Traceable Accounts at the end of each Chapter. This is the description from the NCA5:

Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team's expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

The Traceable Accounts for each Chapter and Key Message includes the following sections:

- Description of Evidence Base
- Major Uncertainties and Research Gaps
- Description of Confidence and Likelihood

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~~The Traceable Accounts are in principle could in principle an important factor in addressing the statutory requirement that the the NCA's statutory requirement to discuss scientific uncertainties. They could also Further, the Traceable Accounts can help satisfy the Executive Order for Restoring Gold Standard Science with regards to by addressing reproducibility, transparency, communication of error and uncertainty, and skepticism of findings and assumptions. However, the execution of the Traceable Accounts in NCA5's Chapters 2 and 3 (the only chapters investigated here) are is uneven, often superficial and noninformative, in Chapters 2 and 3 (which were the only Chapters investigated here).~~

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~~An example of a deficient Traceable Account is NCA5's Here is an example from Key Message 2.2: "Extreme Events are Becoming More Frequent and Severe".~~

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~~The "Description of the Evidence Base" consists offers of two paragraphs, with the first paragraph summarizing the findings and the second paragraph providing a generically describing ption of the types of data that can be used for storms. "Major Uncertainties and Research Gaps" focuses on the uneven distribution across U.S. populations due to differences in exposure and vulnerability. The only limitations in data referred to are the lack of a long-term record of lightning and the lack of homogenized daily and hourly temperature data apart except from reanalysis products.~~

~~But, the most astonishing deficiency is in the "Description of Confidence and Likelihood." One of the statements in Key Message 2.2 is:~~

~~Hurricanes have been intensifying more rapidly since the 1980s (high confidence) and causing heavier rainfall and higher storm surges (high confidence).~~

~~The Description of Confidence and Likelihood includes the following statement:~~

~~Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the~~

authors also have high confidence that storms are delivering more rainfall and high confidence that storm surges are becoming higher.

No reference to journal publications or a specific data set is made in the Chapter regarding hurricane induced precipitation or storm surge to support this *high confidence* conclusion.

~~The Traceable Accounts for the various Key Findings of Chapter 3. With regards to Chapter 3, there are have some substantial inconsistencies between the Traceable Accounts for the different Key Findings. Consider:~~

Key Message 3-1: Human activities have caused global warming.

Confidence and Likelihood: "There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have *unequivocally* caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over this period."

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~~The Uncertainties section only addresses only uncertainties in radiative forcing by of greenhouse gases. By In contrast, the Traceability Analysis of contrast, consider Key Message 3-4 (": "Humans Are Changing Earth System Processes.") is The Traceability Analysis in this section contains arguably the most scientifically credible text in the entire Chapter. From its Description of Evidence Base:~~

In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals.

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~~And From its Major Uncertainties and Research Gaps:~~

For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

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~~There is also a generic problem in tracing NCA5's Traceable Accounts. The Front Matter of NCA5 states: As part of the Traceable Account:~~

"Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation."

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Upon clicking on the eyeball icon above a particular figure, a "Contact Us" email appears, addressed to the USGCRP. No attempt was made to send a email to elicit the Metadata information, but it is clear that this information is not readily accessible online.

In summary, the Traceable Analyses examined here, with few exceptions, fail to meet the stated objectives set forward by the NCA.

6 OVEREMPHASIS ON EXTREME SCENARIOS

To respond to the GCRA mandate to “project major trends for the subsequent 25 to 100 years,” the NCA5 relies on projections of future climate change based on estimates of future emissions (the so-called SSP scenarios) and/or specified levels of radiative forcing (the RCP scenarios). For the most part, NCA5 uses scenarios developed for the IPCC Assessment Reports.

In CWG Section 3.2.1 we presented a critical assessment of past and current IPCC scenario envelopes, showing that they have tended to overshoot observed emissions. The IPCC AR6 published in 2021 stated that “The likelihood of high-emission scenarios like RCP8.5 and SSP5-8.5 is considered low in light of recent energy sector developments.” and that same year in 2021, UN Climate Negotiators (COP) stopped using scenarios above 4.5.

NCA5 makes the following observations about the scenarios they use:

“NCA5 authors were advised to assess the full range of scenarios available.” (Front Matter)

“Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that the highest scenario, SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency.” (Key Message 3.3 Traceable Analysis)

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Despite acknowledging the ~~issue~~issue, the NCA5 otherwise ignored the problem. A keyword search of the NCA5 of mentions of RCP/SSP scenarios finds over 50% referred to the extreme emissions scenarios RCP8.5/SSP5-8.5. Further, 10 NCA5 figures (5.2, 6.9, 7.4, 11.3, 14.6, 22.13, 22.19, 27.9, 29.13) ~~included only~~ included the 8.5 scenarios: 5.2, 6.9, 7.4, 11.3, 14.6, 22.13, 22.19, 27.9, 29.13.

The problem of relying on extreme scenarios is particularly acute for NCA5’s sea level rise projections. The sea level rise scenarios used in the NCA5 do not relate directly to the SSP emissions scenarios, but rather to specified amounts of sea level rise by 2100. Table 4 of NCA5’s “Guide to Using this Report” reproduced below shows that, whereby Low relates to 0.3 m (0.98 feet), Intermediate-Low relates to 0.5 m (1.64 feet), Intermediate relates to 1.0 m (3.28 feet), Intermediate-High relates to 1.5 m (4.92 feet), and High relates to 2.0 m (6.56 feet). (Table 4 of Guide to Using this Report).

Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5						
Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawaii and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2017. ¹⁸						
Sea Level Rise Scenario Descriptor	Global Mean Sea Level			United States		
Year	2050	2100	2150	2050	2100	2150
Low	0.49 (0.15)	0.98 (0.3)	1.31 (0.4)	0.59 (0.18)	0.98 (0.3)	1.64 (0.5)
Intermediate-Low	0.66 (0.20)	1.64 (0.5)	2.62 (0.8)	0.75 (0.23)	1.64 (0.5)	2.95 (0.9)
Intermediate	0.92 (0.28)	3.28 (1.0)	6.23 (1.9)	0.89 (0.27)	3.28 (1.0)	6.89 (2.1)
Intermediate-High	1.21 (0.37)	4.92 (1.5)	8.86 (2.7)	1.12 (0.34)	4.92 (1.5)	8.86 (2.7)
High	1.41 (0.43)	6.56 (2.0)	12.14 (3.7)	1.38 (0.42)	6.56 (2.0)	12.46 (3.8)

CAPTION NEEDED Table 4 from the Front Matter of NCA5

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The text following is Judy's latest edit:

Considering only projections representing processes quantified with at least medium confidence, the IPCC AR6 assessed global mean sea level projections for 2100 to fall between 0.2 and 1.6 m (5th–95th percentile range). Nevertheless, the range of sea level rise scenarios considered by the NCA5 extends to 2.0 m. Further, the NCA5 neglects fails to include plausible lower scenarios, such as 0.2 m cited by the IPCC, which also corresponds to the average rate of sea level rise over the past century.

Chapter 9 of NCA5 offers the following predictions of sea level rise:

"Under a range of potential global warming levels, average sea level along US coastlines is likely to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2)."

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These values span from the Intermediate scenario to values slightly greater than the High scenario. They can be put into context by considering the [HYPERLINK "https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level"] global sea level rise from 2000–2024, approximately 3.39 inches (0.28 feet). NCA5 is thus projecting a sea level rise during 2025 and 2050 that is 3.5 to 5.8 times the rate observed during 2000–2024. With regards to actual predictions of sea level rise, Chapter 9 of the NCA states: "Under a range of potential global warming levels, average sea level along US coastlines is likely to be between 12 and 20 inches above 2000 sea levels in 2050." These values of sea level rise encompass the Intermediate scenario to values slightly higher than the High scenario from NCA5 Table 4 shown above.

Global sea level rise projections to 2050 relative to a 2000 baseline can be evaluated with respect to the observed global sea level rise from 2000–2024, which is approximately 3.39 inches (0.28 feet). [HYPERLINK "https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level"]

Hence NCA5 is projecting values of sea level rise between 2025 and 2050 that are 3.5 to 5.8 times the rate observed during 2000–2024.

Chapter 9 further states:

"Looking toward the future, an 11 inch (28 cm) average rise along the contiguous US coastline is expected by 2050 (relative to 2020), with a *likely* range of 9-13 inches."

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With regards to confidence levels, NCA5 Chapter 9 Traceable Accounts states: "There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (likely range of about 9–13 inches) between 2020 and 2050"

~~In summary, NCA5 presents future sea level rise scenarios that are not directly relatable to either SSP/RCP emissions scenarios nor to global warming levels. The NCA5 scenarios include two scenarios that are higher than the 95th percentile for the extreme emissions scenario RCP8.5 and include hypothesized ice sheet processes in which there is low confidence. Projections to 2050 require rates of sea level rise from 2025 to 2050 that are more than triple the rate observed during 2020-2024. Further, NCA5 ascribes *high confidence* to these sea level rise projections.~~

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~~In summary, the NCA5 presents future sea level rise scenarios that are not directly relatable either to SSP/RCP emissions scenarios or Global Warming Levels. The NCA5 scenarios include some that are higher than the 95th percentile for the extreme emissions scenario RCP8.5 that include hypothesized ice sheet processes for which there is low confidence. Projections to 2050 require rates of sea level rise from 2025 to 2050 that are more than three times the rate observed during 2020-2024. Further, the NCA5 ascribes *high confidence* to these sea level rise projections.~~

~~In summary, the~~ More generally, NCA5's inclusion, and even the focus, on implausible extreme emissions scenarios supports projections of alarming impacts that are very unlikely to be driven by anthropogenic warming.

~~7~~ INADEQUATE NASEM REVIEW: TO BE ADDED

~~7~~ ~~THINK WE SHOULD DELETE THIS CHAPTER. IT ISN'T VERY STRONG~~

The National Academies of Science, Engineering and Medicine (NASEM) undertook a detailed review of the draft NCA5 (NASEM 2023).⁷ While they raised some of the ~~same concerns that we have articulated herein~~, their review is superficial overall and appears to be written by authors who share many of the activist biases of the NCA5 team. There is an inordinate focus on ~~on~~ social and policy issues (e.g., every chapter is assessed under the heading "Comments on Equity and Justice"), rather than on the underlying science. In our assessment NASEM failed to apply the serious rigor one would expect. A few extracted comments from it will illustrate. Note that NASEM review comments are included here in blue font for reference.

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7.1 Substantive criticisms by NASEM

- summarize the valid points made by NASEM and check the NCA replies

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⁷ National Academies of Sciences, Engineering, and Medicine. 2023. *Review of the Draft Fifth National Climate Assessment*. Washington, DC: The National Academies Press. [HYPERLINK "<https://doi.org/10.17226/26757>"].

7.2 Failures to challenge NCA5 flaws

NASEM praised Chapter 2, saying:

The chapter [2] meets the requirements of Section 106 of the GCRA.

Yet contrary to the requirements of Section 106, ~~the NCA5 Chapter 2 did not adequately~~ not discuss natural variability let alone assess the full climate record available for quantifying natural variability. Chapter 2 actually minimizes natural variability by claiming (unsubstantiated) skill in attributing recent extremes to human causes. For example NCA5's Chapter 2 Introduction states,

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"...recent advances in attribution science (KM [[HYPERLINK "https://nca2023.globalchange.gov/chapter/3"](https://nca2023.globalchange.gov/chapter/3) \l "key-message-3" \t "_blank"]) mean that the role of climate change in some extreme events can now be quantified in real time. For example, climate change made the record-breaking Pacific Northwest heatwave of June 2021 2° to 4°F hotter, and in 2017 ..."

CWG25 reviews the expert literature demonstrating that this particular event would have happened with or without climate change and that for the CONUS, hot extremes are no more frequent now than they were in the past. NASEM did not challenge the unsubstantiated attribution claims in the NCA5.

Notwithstanding NASEM's claim that the Chapter complies with Section 106 of the GCRA, it then acknowledged the absence of discussion of natural variability:

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...the discussion and references regarding the role of natural climate variability and its regional differences are missing.

While a nod to natural variability is occasionally found in NCA5, it is usually followed by a "however" to emphasize human influence. One example is the statement just before the claim mentioned above pertaining to extreme event attribution: "There has always been extreme weather, which occurs even in an unchanged climate due to the natural variability of the Earth system. However, recent advances in attribution science (KM [[HYPERLINK "https://nca2023.globalchange.gov/chapter/3"](https://nca2023.globalchange.gov/chapter/3) \l "key-message-3" \t "_blank"]) mean that the role of climate change in some extreme events can now be quantified in real time..."

We pointed REFERENCE THE SPECIFIC SECTION OF THIS REPORT out that the evidence regarding heatwaves directly contradicts Key Message 2.2. NASEM did not mention this, instead it focused on a somewhat esoteric issue of terminology:

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"Extreme Events Are Becoming More Frequent and Severe."

Key Message 2.2 is another generally well written key message. However, while the title of this key message includes the word "risk," the key message is exclusively about hazard. The Committee suggests rewriting the key message title to more accurately reflect the discussion on hazards.

The NASEM review appears to accept the NCA5's use of short data records because it makes no critical remarks about the failure to assess long time series, except for its observation that the use of short records makes the omission of natural variability that much more of a problem:

It is also important to point out that the influence of natural climate variability becomes particularly strong when the climate trend is computed based on short periods of time or small geographic areas.

This comment was largely ignored in the NCA5 final text.

In sum, while the NASEM review might bestow the Academies' imprimatur on the NCA5 report, it does not necessarily add to its quality for two reasons. As we have demonstrated, the NASEM review falls short in rigor and completeness. And second, the NCA authors are not obligated to follow the NASEM recommendations in crafting their final product.

8 SUMMARY: EVALUATION OF THE NCA5

~~CHAPTER NEEDS A COMPLETE REWRITE~~

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~~The most straightforward evaluation of NCA5 is through its statutory requirements. While it is not within our purview to make definitive rulings on compliance, we believe there are several important aspects to consider when evaluating NCA5 against its statutory requirements. Add text per Seth's letter ...~~

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~~Our expertise in climate science, the foundational area covered by NCA5, allows a different perspective one that finds the coverage unbalanced and selective. Our review has identified numerous instances where NCA5 falls short of the quality and integrity expected of scientific document of this importance. Furthermore, our examination suggests that the entire process—from the selection of contributing authors to the handling of expert reviews—appears to have been systematically biased toward reinforcing predetermined conclusions and amplifying alarmist messaging rather than presenting a balanced scientific assessment. In short, NCA5 was written to persuade, not inform.~~

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~~A third perspective for evaluating NCA5 is that of citizens interested in good policymaking. The changing climate is a legitimate public concern, as are concerns about cost of living, economic growth, employment opportunities, and other socioeconomic factors. We share the widespread belief that elected officials should have access to the highest quality information when crafting energy and climate policy decisions that must balance multiple concerns. From this perspective, NCA5 is a missed opportunity. What could have been a valuable contribution to informed tradeoffs instead became a misleading advocacy document that corrupts the policymaking process.~~

~~PERTINENT ASPECTS WHEN EVALUATING NCA5 IN LIGHT OF STATUTORY REQUIREMENTS~~

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~~—NOT OUR REMIT TO MAKE A RULING BUT HERE ARE ASPECTS TO CONSIDER IN LIGHT OF STATUTORY REQUIREMENTS~~

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~~8.1 —EVALUATION FROM THE PERSPECTIVE OF EXPERT USERS OF THE REPORT~~

~~—WE HAVE DEEP KNOWLEDGE OF THE TOPICS SURVEYED BY THE NCA5 AUTHORS~~

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~~-WE DO NOT HAVE CONFIDENCE THAT THE REPORT WAS BALANCED AND COMPREHENSIVE~~

~~-WE CAN POINT TO MANY SPECIFIC INSTANCES IN WHICH THE REPORT DID NOT EXHIBIT AN APPROPRIATE LEVEL OF QUALITY OR INTEGRITY AS A SCIENTIFIC DOCUMENT~~

~~-WE HAVE REASON TO BELIEVE THE WHOLE PROCESS, FROM AUTHOR SELECTION TO HANDLING OF EXPERT REVIEWS, WAS BIASED TOWARDS REINFORCING FOREGONE CONCLUSIONS AND ALARMIST MESSAGING~~

~~8.2 EVALUATION FROM THE PERSPECTIVE OF CITIZENS INTERESTED IN GOOD POLICYMAKING~~

~~-PUBLIC CONCERNS ABOUT CLIMATE CHANGE ARE VALID, AS ARE CONCERNS ABOUT COST OF LIVING, ECONOMIC GROWTH, EMPLOYMENT, ETC.~~

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~~-WE SHARE THE GENERAL CONCERN THAT ELECTED OFFICIALS AND THOSE WHO SERVE THEM HAVE THE BEST INFORMATION AVAILABLE WHEN MAKING IMPORTANT DECISIONS AROUND ENERGY AND CLIMATE POLICY~~

~~-NCA5 WAS A MISSED OPPORTUNITY: IT COULD HAVE BEEN A VALUABLE INPUT TO THAT PROCESS BUT IT DID NOT TURN OUT THAT WAY~~

~~-CONSEQUENTLY ITS USAGE IS UNLIKELY TO LEAD TO BETTER DECISIONS AND WOULD MORE LIKELY INCREASE THE ERROR RATE IN POLICY FORMATION AND WE RECOMMEND IT NOT BE USED FOR POLICYMAKING PURPOSES.~~

APPENDICES

APPENDIX 1: Charge to the review

APPENDIX 21: Seth's letter on statutory requirements for NCA5NCA5

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APPENDIX 32: Analysis of 141 U.S. Longterm Daily Precipitation Records.

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I'm not sure we need both the tables and multipanel figures here. Is anyone really going to look at the tables? Perhaps they can be eliminated and just keep the figures?

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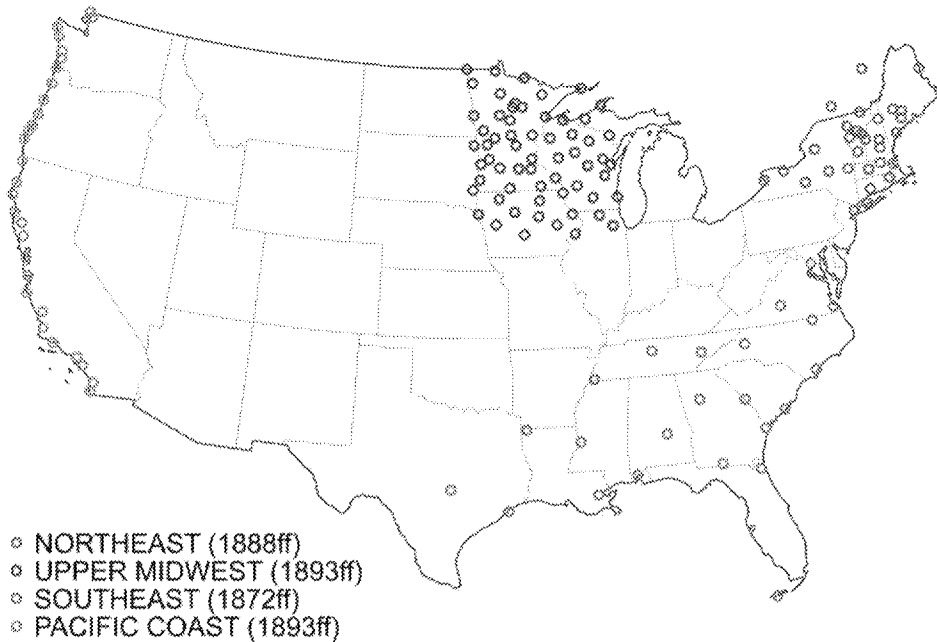


Figure. Stations used in the following analyses.

Table codes: (-) neg insignificant, -- neg significant, (+) pos insignificant, ++ pos significant.

Column 1: Measure

Column 2: Number of stations in that region

Column 3: Count of stations exhibiting a significant positive trend

Column 3: Count of stations exhibiting a significant negative trend

Column 5: Characteristic of region-wide trend

PACIFIC COAST

Since 1893:

	No. stns	+ trends	- trends	region
1-day average	29	0	1	(-)
2-day average	29	0	1	(-)

Avg on non-zero days	29	0	9	--
Variability	29	1	0	(+)
Annual max	29	2	1	(+)
Number of 99 th pct exceedances	29	1	0	(-)

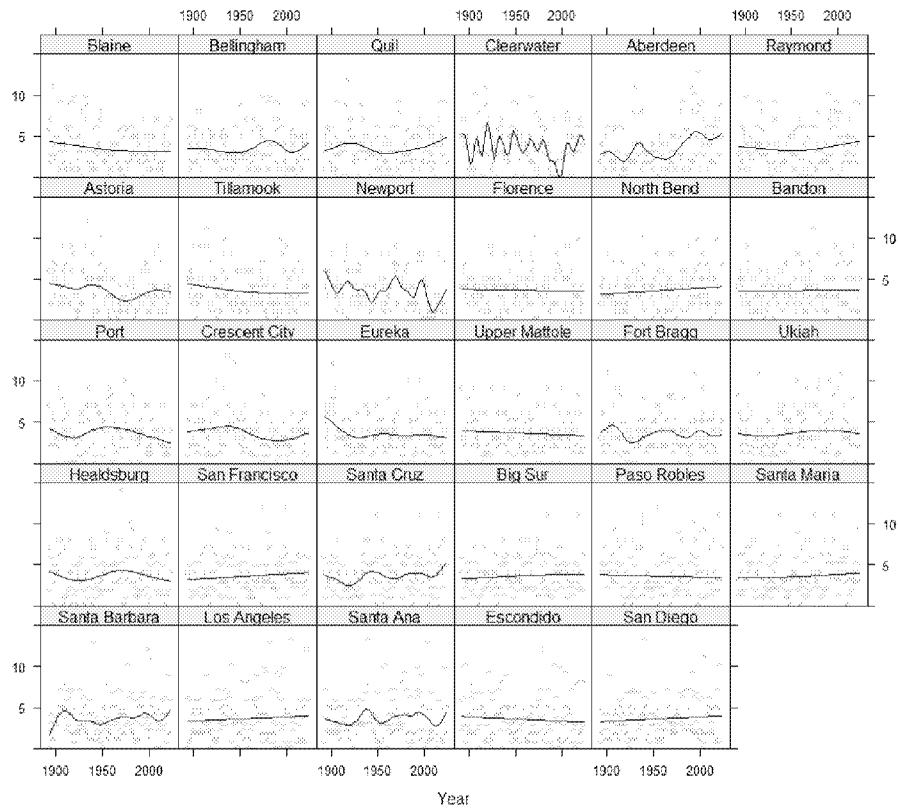
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	29	0	1	(-)
2-day average	29	0	1	(-)
Avg on non-zero days	29	0	4	(-)
Variability	29	2	3	(-)
Annual max	29	6	3	(-)
Number of 99 th pct exceedances	29	2	1	(-)

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	29	0	0	(-)
2-day average	29	0	0	(-)
Avg on non-zero days	29	0	1	(-)
Variability	29	0	0	(-)
Annual max	29	2	1	(-)
Number of 99 th pct exceedances	29	0	0	(+)

Annual No. 99th Percentile Exceedances PC 1893-2024



SOUTHEAST

Since 1873:

	No. stns	+ trends	- trends	region
1-day average	24	1	1	(+)
2-day average	24	1	1	(+)
Avg on non-zero days	24	7	2	(+)
Variability	24	1	0	(+)
Annual max	24	2	0	(+)
Number of 99 th pct exceedances	24	5	0	(+)

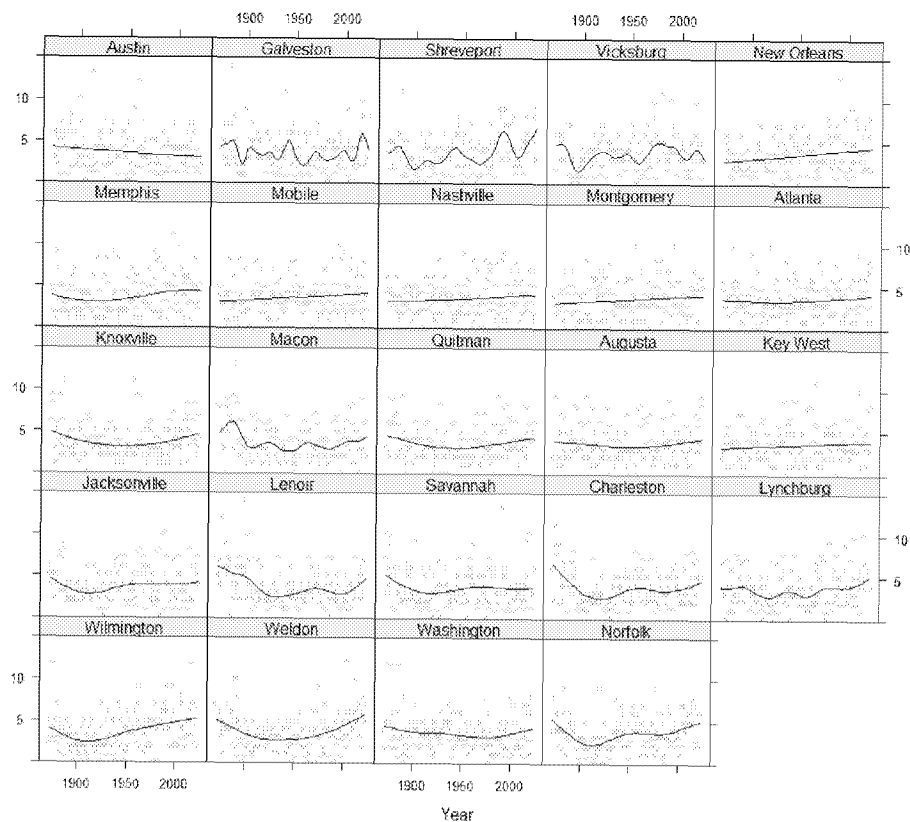
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	24	5	0	++
2-day average	24	5	0	++
Avg on non-zero days	24	5	1	++
Variability	24	6	0	++
Annual max	24	4	0	++
Number of 99 th pct exceedances	24	4	0	(+)

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	24	5	0	(+)
2-day average	24	5	0	(+)
Avg on non-zero days	24	5	1	(+)
Variability	24	3	0	(+)
Annual max	24	4	0	(+)
Number of 99 th pct exceedances	24	4	0	(+)

Annual No. 99th Percentile Exceedances SE 1873-2024



MIDWEST

Since 1893:

	No. stns	+ trends	- trends	region
1-day average	61	23	0	++
2-day average	61	23	0	++
Avg on non-zero days	61	2	12	(+)
Variability	61	12	0	++
Annual max	61	9	0	(+)
Number of 99 th pct exceedances	61	10	0	(+)

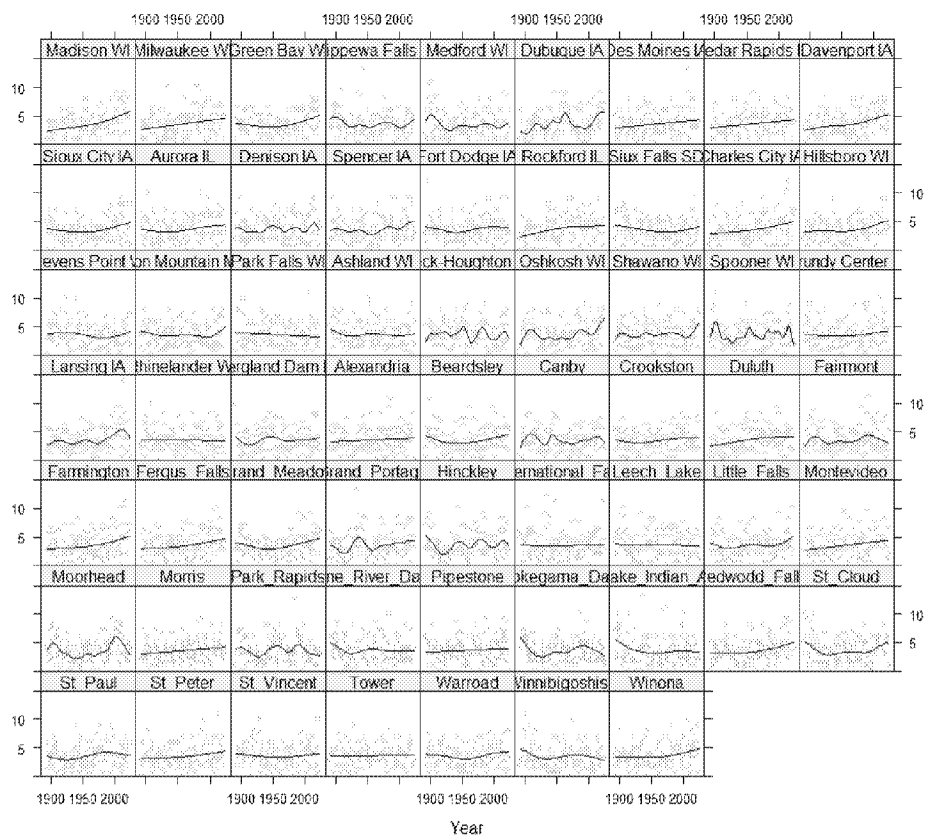
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	61	28	2	++
2-day average	61	28	2	++
Avg on non-zero days	61	11	1	++
Variability	61	16	0	(+)
Annual max	61	8	0	(+)
Number of 99 th pct exceedances	61	19	0	++

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	61	6	1	(+)
2-day average	61	6	1	(+)
Avg on non-zero days	61	8	2	(+)
Variability	61	5	1	(+)
Annual max	61	0	1	(+)
Number of 99 th pct exceedances	61	5	3	(-)

Annual No. 99th Percentile Exceedances MW 1893-2024



NORTHEAST

Since 1888:

	No. stns	+ trends	- trends	region
1-day average	27	12	0	++
2-day average	27	12	0	++
Avg on non-zero days	27	7	1	(+)
Variability	27	4	0	(+)
Annual max	27	3	0	(-)
Number of 99 th pct exceedances	27	5	0	(+)

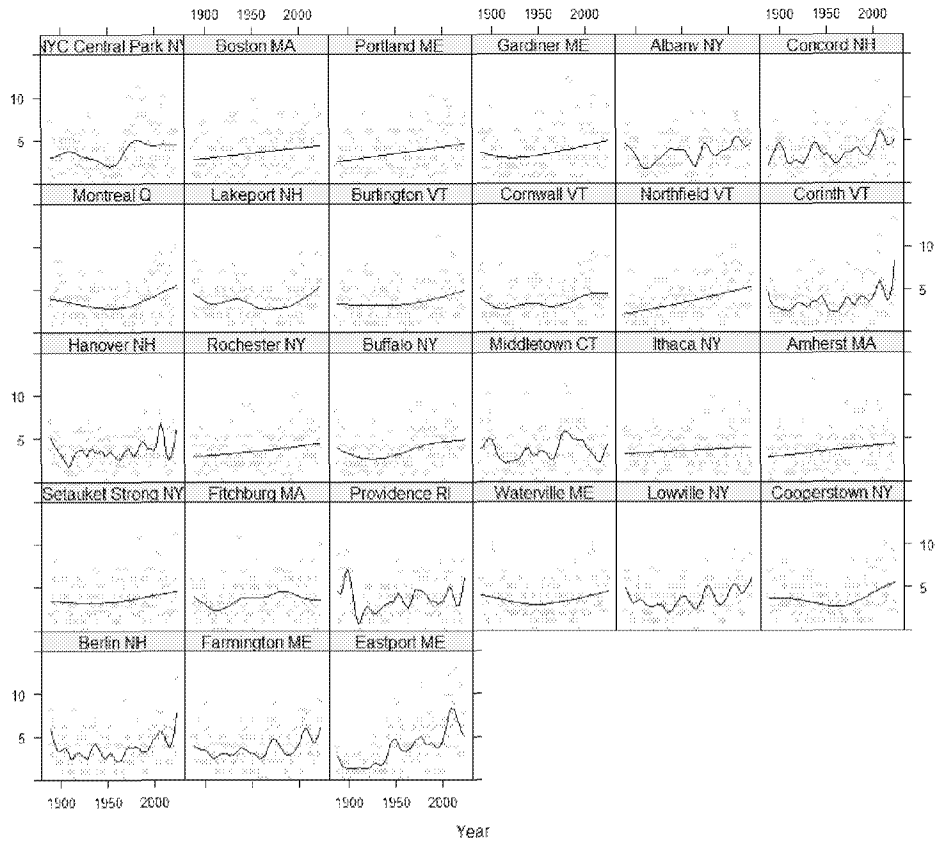
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	27	12	0	++
2-day average	27	12	0	++
Avg on non-zero days	27	7	1	(+)
Variability	27	4	0	(+)
Annual max	27	3	0	(-)
Number of 99 th pct exceedances	27	5	0	++

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	27	10	1	++
2-day average	27	10	1	++
Avg on non-zero days	27	6	0	(+)
Variability	27	2	0	(+)
Annual max	27	1	0	(+)
Number of 99 th pct exceedances	27	1	1	++

Annual No. 99th Percentile Exceedances NE 1888-2024



ABOUT THE AUTHORS

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Chapter 10 RISK AND ITS ASSESSMENT

“[I]n itself, nothing is a risk, there are no risks in reality. Inversely, anything can be a risk; it all depends on how one frames the danger, considers the event.” – French philosopher François Ewald¹

The concept of risk is an outgrowth of concerns about coping with dangers. For most of human history, the assessment and management of risk occurred informally by trial and error. More than 2400 years ago, Athenians articulated the capacity of assessing risk before making decisions.² However, as the influence and scale of technology expanded, it became evident that society needed to assess risks proactively. Science has increasingly allowed us to recognize and measure more subtle hazards, which has been coupled with a general decreasing tolerance for risk in modern industrialized society.³

Risk assessment and management as a scientific field is only about 30–40 years old. There are many different perspectives on risk, and some of these perspectives represent substantially different frameworks. However, there is broad agreement on the basic ideas and principles of risk understanding, assessment, communication and management.⁴

Risk may have positive or negative outcomes or may simply result in uncertainty. Fire and accidents only have negative outcomes, and they are often referred to as hazard risks. Taking a risk can also result in a positive outcome. Risk can also be related to uncertainty of outcome. However, most applications of risk analysis focus on adverse outcomes.

Climate change presents a challenge to risk assessment that is uniquely complex, uncertain and ambiguous. This chapter provides perspectives on risk and its perception, how risk is

characterized and analyzed, and why climate change is such a challenging problem for risk analysis.

10.1 Risk and Perception

“You are so convinced that you believe only what you believe that you believe, that you remain utterly blind to what you *really* believe without believing you believe it.”

— American writer Orson Scott Card⁵

Climate risk is generally regarded as hazard risk, although there are potential positive outcomes as well. The related terms “threat” and “hazard” refer to something that could cause harm, with the possibility of trouble, danger or ruin.⁶ The hazard may be something that is impending and imminent, or something that is likely, or merely possible. A forecasted extreme weather event is an imminent, impending hazard. For climate change supported by scenarios from global climate models or expert assessments, *likely* is the descriptor in IPCC parlance. Possibility is used for military threats and threats to cybersecurity, based on creatively imagined scenarios.

Risk has often been characterized as some type of statistical expected value – the product of the likelihood of occurrence and the impact if it occurs. However, such a characterization is appropriate only for simple or tame problems. Broader definitions of risk integrate specified consequences of an event or actions, a measure of uncertainty associated with the consequences, and the strength of the background knowledge that supports the assessment.⁷

The IPCC defines climate change risk through the dynamic association of the three core elements of risk: hazard, exposure and vulnerability. Hazard captures the frequency and intensity of extreme weather and climate events or slowly emerging change such as sea level rise. Exposure

refers to the elements of populace, infrastructures and social welfare at risk. Vulnerability refers to the exposures' potential to suffer as well as its ability to manage, withstand and rebound.^{8]}

The main concerns surrounding the consequences of manmade global warming are described below:⁹

Commented [MJ1]: The IPCC (2011) defines climate change risk as a function of three core elements: hazard, exposure and vulnerability. Hazard refers to the frequency and intensity of extreme weather and climate events or slowly emerging change such as sea level rise. Exposure refers to the exposure of the population, infrastructures and social wealth to the risk. Vulnerability refers to the vulnerability of a system to the risk, as well as its ability to cope, resist and recover.

- 1) Risk of death, injury, ill health or disrupted livelihoods in low lying coastal zones and small island developing states due to storm surges, coastal flooding and sea level rise;
- 2) Risk of severe ill health and disrupted livelihoods for large urban populations due to inland flooding;
- 3) System risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply and health and emergency services;
- 4) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas;
- 5) Risk of food insecurity and the breakdown of food systems linked to warming drought flooding and precipitation variability and extremes, particularly for poorer populations in urban and rural settings;
- 6) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions;
- 7) Risk of loss of marine and coastal ecosystems, biodiversity and ecosystem goods, functions and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic; and

- 8) Risk of loss of terrestrial and inland water ecosystems, biodiversity and the ecosystem goods, functions and services they provide for livelihoods.

As evidenced from this list, risks from human-caused climate change are convoluted with natural weather and climate variability, and are dominated by societal vulnerabilities in context of developing states and poorer populations.

10.1.1 Risk perceptions

“Something frightening poses a perceived risk. Something dangerous poses a real risk.” – Swedish physician Hans Rosling et al.¹⁰

Apart from the objective facts about a risk, the social sciences find that our interpretation of those facts is ultimately subjective. Risk science makes a clear distinction between professional judgments about risk versus the public perception of risk. Risk perception is a person’s subjective judgement or appraisal of risk, which can involve social, cultural and psychological factors.

No matter how strongly we feel about our perceptions of risk, we often get risk wrong. People worry about some things more than the evidence warrants (e.g. vaccines, nuclear radiation, genetically modified food), and less about other threats than the evidence warrants (e.g., obesity, using mobile phones while driving). This gap in risk perception produces social policies that protect us more from what we are afraid of than from what actually threatens us the most. Understanding the psychology of risk perception is important for rationally managing the risks that arise when our subjective risk perception system gets things dangerously wrong.¹¹

The Psychometric Paradigm research of psychologist Paul Slovic and collaborators describes a suite of psychological characteristics that make risks feel more or less frightening, relative to the actual facts^{12 13 14}

- natural versus manmade risks
- risks that are detectable versus undetectable (without special instrumentation)
- controllable versus uncontrollable risks
- voluntary versus imposed risks
- risks with benefits versus uncompensated risks
- known risks versus vague risks
- risks central to people's everyday lives versus uncommon risks
- future versus immediate risks
- equitable versus asymmetric distribution of risks.

In each of these pairs, the first risk type is generally preferred to the second risk type. For example, risks that are common, self-controlled and voluntary, such as driving, generate the least public apprehension. Risks that are rare and imposed that lack potential upside, like terrorism, invoke the most dread.¹⁵

Commented [MJ2]: Uncommon, imposed risks without benefits, such as terrorism, inspire the most dread.

Communicators hoping to spur action on climate change emphasize the manmade aspects of climate change, the unfair burden of risks on undeveloped countries and poor people, and the more immediate risks of severe weather events. The recent occurrence of infrequent events (e.g. a hurricane or flood) produces disparate perceptions of the risk of low probability events, that translate into perceptions of overall climate change risk.

The cultural theory of risk proposes that individual views on risk are filtered through cultural world views about how society should operate.¹⁶ People tend to relate their position on the environmental risk spectrum with how they perceive nature. Risk seekers view nature as robust, while risk avoiders see nature as fragile. In between can be found risk regulators that see a robust nature with bounds, leaving those who are indifferent to risk who view nature as unpredictable and view risk truly as just chance.¹⁷

Commented [MJ3]: Some people have a risk-seeking attitude whereas others have a risk-averse attitude. Environmental risk attitudes tend to correlate with the way that people view nature. Those that see nature as robust tend to be risk-seeking, those that see nature as fragile tend to be risk-averse. In between are those that have a risk-regulating attitude, corresponding to a view of nature as 'robust within limits', and those that are indifferent to risk, corresponding to a view of nature as capricious or risk as fate.

Even if the initial harm is small, the social risk may be greatly amplified by the collective response or irrational behaviors of individuals. The response to climate risk, driven by alarmism and “extinction” rhetoric, has arguably crossed the threshold to actually increasing the social risk associated with climate change.

10.1.2 Risk characterization

“We must see these things objectively, as we do a tree; and understand that they exist whether we like them or not. We must not try and turn them into something different by the mere exercise of our own minds, as if we were witches.” – English writer and theologian G.K. Chesterton¹⁸

The concept of hazard risk captures both the threat contribution and vulnerability to the threat. Risk can be split into two main components: i) occurrence of the triggering events and associated uncertainties; and ii) consequences, given the events, and the associated uncertainties.

The concept of resilience is closely related to vulnerability. Resilience is defined as the ability of the system to maintain functionality and recover, given that one or more triggering events occur.

The ability—or lack of ability—of impacted systems to maintain performance and recover from the event will determine the consequences of the event.

An important element of characterizing risk is evaluating the strength of knowledge (Section 9.3). Concerns about strength of the knowledge base are raised by people questioning aspects of the IPCC's assessment that are used to infer climate risk. The IPCC approach is based on judgement of the available evidence and agreement among experts. More sophisticated knowledge characterizations for risk management include:¹⁹

- (i) the degree to which the assumptions made are reasonable/realistic based on our background knowledge – growing concern about the focus on implausible emissions scenarios RCP8.5/SSP5-8.5 (Section 7.1)
- (ii) the degree to which data/information exists and are reliable and relevant – the historical and paleo data base is inadequate for a complete characterization of natural climate variability on multi-decadal to millennial time scales
- (iii) the degree to which there is disagreement among experts (including those from different environments) – attempts to suppress disagreement and alternative perspectives among experts (Section 2.4)
- (iv) the degree to which the phenomena involved are understood and accurate models exist – concerns about the fidelity and utility of climate models (Chapter 6)
- (v) the degree to which the knowledge has been thoroughly examined with respect to unknown knowns – neglect of the unknown knowns associated with natural climate variability (Section 8.2).

Accepting the IPCC's assessments as the best available knowledge base is not inconsistent with acknowledging significant weaknesses in the knowledge base in context of climate risk analysis.

There are various types of risk, independent of the nature of the triggering event or the consequence. In 1921, economist Frank Knight articulated a definition of risk that distinguished risk from uncertainty.²⁰ Knightian risk implies that robust probability information is available about future outcomes, allowing risks to be treated in terms of probability and effects. Knightian risk underlies the technocratic, decisionistic and economic models of risk assessment and management.²¹ Similarly, mathematician Benoit Mandelbrodt differentiates between "mild" and "wild" risk.²² Systems that are predictable, have large quantities of sample cases to explore and that conform to normal style distributions would be considered mild. In contrast, random behavior, unusual distributions and largely unpredictable systems fall into the wild realm.²³ The danger lies in making the assumption a risk is mild when it is indeed wild.

Knightian-based, or mild, risk assessment and management is suited to simple, or tame, problems (Section 3.4). For simple risks, the cause for the risk is well known, the negative consequences are obvious, and randomness is low. The risk consequences are reversible and are well understood in terms of the science and regulation. Simple risks are recurrent and not affected by ongoing or expected major changes; hence, assessing the risks in statistical terms is meaningful. Examples include car accidents and regularly recurring weather hazards – hazards that insurance companies have traditionally covered.

Simple risks are characterized by low complexity, low uncertainty and low ambiguity. However, the most worrisome risks are not associated with simple problems. Wild risks are associated with high uncertainty and even ignorance. Complexity gives rise to systemic risk. Related to the

Commented [MJ4]: Mild risk follows normal or near-normal probability distributions and is subject to regression to the mean and the law of large numbers and therefore relatively predictable. Wild risk has a large degree of randomness and follows fat-tailed distributions, rendering the law of large numbers ineffective and is therefore difficult or impossible to predict. A common error in risk assessment and management is to underestimate the wildness of risk, assuming risk to be mild when in fact it is wild.

term “mess” that was introduced in Section 3.4, “ambiguity” means that there are different legitimate viewpoints from which to evaluate whether there are, or could be, adverse effects and whether these risks are tolerable. Ambiguity results from divergent and contested perspectives on the justification, severity or wider meanings associated with a perceived threat.²⁴

Some example types of risk that are not simple:²⁵

- Combination of low probability with high extent of damage. This includes technological risks associated with nuclear power plants or dams.
- Disaster potential is high and relatively well known, but little is known about causal factors. Earthquakes and volcanoes are examples.
- Human interventions in the environment that cause wide-ranging, persistent and irreversible changes, which are discovered after the interventions. Examples include large infrastructure projects such as dams and river engineering.
- There is a considerable delay between the triggering event and the occurrence of damage. Fossil fuel emissions are an example.

Risk conceptions can also be usefully categorized based on future predictability – the extent to which historical records are useful in assessing the risk of a future outcome.²⁶ When there is a clear causal relationship, the past can be a very good predictor of the future. However when uncertainty prevails the past is not a good indicator of the future and unprecedented outcomes can occur.²⁷

The concept of emerging risk is gaining increasing attention. Emerging risk is related to an activity when the background knowledge is weak but contains indications/justified beliefs that a new type of event could occur in the future and potentially have severe consequences to

something humans value. The weak background knowledge results in difficulty specifying consequences and as well in specifying scenarios.²⁸ Intergenerational impacts are a concern with emerging risks. Global warming is clearly an emerging risk. An important consideration when thinking about emerging risks is the speed at which they can become significant, which is referred to as the risk velocity.

Climate change risk includes elements of both incremental risk and emergency risk. Incremental risk displays creeping characteristics and the “fat tail” effect. Since changes take place rather slowly, the adverse consequences take a long time to emerge. Some climate impacts are expected to accumulate and worsen over time and across space. The slow creep of sea level rise is an example of incremental risk. A more complex example is the risk of long-term water shortage in Africa, which reduces food production over time and aggravates malnutrition and other health problems, leading to migration and regional violent conflicts. The potential impacts and long-term consequences can easily be underestimated in the early stage. Once incremental risks cross a critical point, they are difficult to manage – this relates to the so-called climate “tipping points” (Section 1.3.2).

Emergency risks are associated with extreme weather events; technically these are weather risks and not climate risks, even if global warming could be shown to incrementally worsen the weather hazard. Weather risk can become climate risk if global warming causes the event to exceed a vulnerability threshold that otherwise wouldn’t have been exceeded by the weather event. Attempts are also made to assess incremental costs/damages associated with extreme weather events. Such assessments are very challenging to make against the background of natural weather and climate variability.

10.1.3 Direct versus systemic risk

“A dike ten thousand feet long begins its crumbling with holes made by ants” –

Chinese philosopher (Zhou Dynasty) Han Fei Tzu²⁹

Direct risks from a hazard arise from a direct impact arising from the driver or event. Examples of direct risk from climate change include: heat stress to people, crop production failures, damage from unusual river flooding, sea level rise for coastal cities. Direct risks can be non-linear – while average conditions may change gradually, the risks can increase more rapidly if critical vulnerability thresholds are exceeded.

The risks of climate change to human interests depend not only on the direct impacts from changes in the physical climate, but also on the response of complex human systems such as the global economy, food markets, and the system of international security. In complex systems, small changes can sometimes lead to large divergences in future state. Systemic risks are characterized by a high degree of complexity, uncertainty, and ambiguity.³⁰ Many problems categorized as a “wicked mess” (Section 3.4) can also be categorized as systemic risks.

The greatest risks associated with climate change are systemic. Systemic risks may arise from the interaction of the climate with complex human systems such as global food markets, governance arrangements and international security. Systemic risks are much less straightforward to assess than direct risks. Systemic risks may be initiated by local stressor such as an extreme weather event, which can have impacts extending far beyond the impacted location. An example of national and international security systemic risk is triggered by regional drought, resulting in migration and displacement, food price spikes, civil unrest, state failure, terrorism, humanitarian crises, and transboundary water disputes.³¹

Hazard events that previously might have caused localized impacts can now have cascading and even global impacts. Consider the severe, widespread flooding in Thailand during 2011. The flooding was triggered by the landfall of a tropical storm, spreading through much of Thailand along the Mekong and Chao Phraya River basins. The systemic nature of this event arose from flooding of the industrial estates and production plants around Bangkok.³²

Apart from cascading effects on Thailand's economy, this local flood ended up having systemic impacts across countries, regions and economic sectors, affecting supply chains as far away as Japan and the United States. Key manufacturing sectors such as the automobile, electronics and electrical appliances industries experienced abrupt declines in production and exports. The disruption caused a global shortage of hard disk drives, which lasted throughout 2012.³³ Components manufactured in Thailand were essential for products finalized in other countries, causing disruption or collapse of the entire production chains.

10.2 Risk Assessment

“When knowledge is uncertain, experts should avoid pressures to simplify their advice.” – science and technology policy researcher Andy Stirling³⁴

Risk assessment is the systematic process of identifying risk sources, threats, hazards and opportunities; understanding how these can materialize/occur; identifying specific trigger events and event sequences, and what their consequences could be; representing and expressing uncertainties; and determining the significance of the risk.³⁵ The role of risk assessment is to support understanding, communication and decision-making processes.

Traditional risk assessment has been based on historic data—assessing probabilities of severity, frequency and impact based on experience from past events. In times of global change, this approach is no longer adequate to capture future risks. Scenarios of future climate and extreme events are generated by models and by storyline approaches (Chapters 7, 8, 9).

Apart from the likelihood and impacts of the risk, values and ancillary issues that contribute to risk perception should be integrated into the risk assessment. Further, risk evaluation requires assessment of risk(s)–benefit(s) and risk–risk trade-offs.³⁶ Risks need to be assessed in context of all of the relevant dimensions that matter to the affected populations.³⁷ A broad assessment of the risk provides a knowledge base so that decision makers have better guidance on how to select measures for managing the risk.

Narrow risk assessments of well-understood phenomena with ample data might be uncontested. However for contentious issues, the outcome of a risk assessment may be strongly influenced by the many inherent value judgments (often unknowingly) made by the analyst. Scientific studies have trouble resolving differences when the value assumption process is murky. Wise policymakers are likely to dismiss overly certain assessments, properly recognizing their biases or naivete. Trust is built via an open dialog around value assumptions, reducing the concerns of hidden agendas.³⁸

Commented [MJ5]: The various forms of value assumptions made in risk assessments are a primary reason for the common inability of scientific studies to resolve disputes. Astute policymakers understand the limitations of risk analysis, and any assessment that is overly conclusive will be dismissed as biased or naïve. Considering and clearly discussing the value-laden assumptions in a risk assessment improves trust in the provided information by allaying concerns of hidden agendas.

10.2.1 Acceptable versus intolerable risk

~~“We must contemplate some extremely unpleasant possibilities, just because we want to avoid them.”³⁹ —American nuclear strategist Albert Wohlstetter~~

NEW QUOTE “Time heals nothing. It only brings other issues and tissues, and takes what is incurable or unacceptable out of the center of our attention.”

— Ana Claudia Antunes, author of [[HYPERLINK](#)

"<https://www.goodreads.com/work/quotes/14234996>"]

An essential aim of risk assessment is to qualify the risks in terms of the social acceptability and tolerability. The “traffic light model” identifies three categories for risks: normal/acceptable risks, intermediate/tolerable risks and intolerable risks.⁴⁰ Normal risks are characterized by low complexity, little statistical uncertainty and low catastrophic potential (Knightian or mild risk), and are well understood by science and easily managed by regulatory mechanisms.⁴¹

Activities are tolerable if they are considered as worth pursuing for the associated benefits. For tolerable risks, efforts for risk reduction or coping are welcomed provided that the benefits of the activities are not lost. Burning fossil fuels has historically been considered a tolerable risk.⁴²

Genuinely intolerable risks include existential threats—such as portrayed by the earth-impacting comet in the movie *Don’t Look Up*—or “ruin” problems.^{43 44}

How to draw the lines between “acceptable”, “tolerable” and “intolerable” is one of the most controversial tasks in the risk governance process for complex risks. Ambiguity results from divergent and contested perspectives on the justification, severity or wider meanings associated with a perceived threat.⁴⁵ Climate change risks have been characterized as acceptable, tolerable and intolerable by different individuals and constituencies – clearly an ambiguous situation.

Using the example of extreme weather risks, fairly routine destruction by hurricanes in certain coastal regions is generally categorized as tolerable, with some locations working to decrease vulnerability over time by improving building codes and engineering the coast to minimize the

impact of storm surge. By contrast, a rare but extreme event such as Superstorm Sandy striking New York City was judged to be associated with intolerable risk and a large adaptation deficit, given the large population and property value that was impacted and high vulnerability of the infrastructure.

For complex problems, often neither the risks nor the benefits can be clearly identified or agreed upon. Multiple dimensions and values need to be considered. A heavily contested assessment of the (in)tolerability or acceptability of risks is highly relevant input to the decision-making process, in context of the ambiguity of the risk.

10.2.2 Assessment of systemic risks

~~“We live on an island surrounded by a sea of ignorance. As our island of knowledge grows, so does the shore of our ignorance.”⁴⁶ — John Wheeler~~

NEW QUOTE “it is not a calculated risk if you haven’t calculated it.”
— Naved Abdali, author of [Investor LINK](#)

In most problems of systemic risk, there are numerous ambiguous and unknown risks. Due to the complexity of systemic risk and the limited understanding of the risk propagation paths, there are substantial uncertainties in terms of the cascading effect of the systemic risk on the influence domain.

Key characteristics of systemic risk are broadly categorized under five themes: the scale of the system, the relationship of the elements within a system, the level of system understanding, the transboundary effects and the outcomes of systemic risk.⁴⁷

An important tool in characterizing systemic risk is forensic analysis of previous disasters.

Forensic analysis combines retrospective longitudinal analysis, disaster scenarios, comparative case analysis and meta-analysis research, along with enhanced involvement of development stakeholders.⁴⁸ Forensic analysis can help better understand how and why disasters occur and their complex linkages with natural, infrastructure and societal systems.⁴⁹

Recognizing the depth of uncertainty about the future state of complex systems, assessment of systemic risk relies on the tools of scenarios and wargaming to help us think about what might happen. A key challenge for systemic risk assessment is to identify key linkages and the potential for critical transitions, in context of how systemic risks cascade through interdependent networks in both physical and social systems.⁵⁰ Complex challenges like pandemics or climate change should be assessed in the global context of megatrends such as urbanization, growing populations, demographic changes, environmental degradation, and technological change.

In risks that go beyond ordinary dimensions, such as COVID-19 and climate change, the reliability of any risk assessment is low, uncertainty is high, catastrophic potential can possibly reach alarming dimensions and systematic knowledge about the distribution of consequences is missing. Such risks may generate global, irreversible damages, which may accumulate during a long time or mobilize or frighten the population; or alternatively, the risks may turn out to be relatively benign. An unequivocal conclusion about the degree of validity associated with the scientific risk evaluation isn't feasible. For such problems, risk assessments are most effectively used as a tool used to represent and describe knowledge and lack of knowledge, and to formulate narratives of possible danger.

10.3 Climate Change Risk

“I have long argued climate messaging needs to be about here and now, kitchen table issues ... not 8 decades from now or way in the Arctic” – meteorologist Marshall Shepherd⁵¹

Many public organizations, ranging from the United Nations to local municipalities, have conducted risk assessments of climate change impacts. There is also a growing trend for private companies with responsibility to shareholders to conduct climate risk assessments. Virtually all of these climate risk assessments are based on assessment reports from the IPCC.

Cumulative risks at national and global levels are linked to the principle of avoiding dangerous climate change as defined by the UNFCCC, which is tied to assumed risk thresholds of +1.5 °C and +2 °C global warming above pre-industrial level. The most recent IPCC reports have formulated a risk-based approach for understanding the risk factors that lead to regional/local climate change impacts, and the role of adaptation initiatives in managing these risk factors. The importance of regional climate change risk assessments is recognized politically through the UNFCCC in context of Warsaw International Mechanism for Loss and Damage and the Sendai Framework for Disaster Risk Reduction under the auspices of the UN Office for Disaster Risk Reduction.^{52 53}

Thus far, government-sponsored climate change assessments have primarily been rooted in communicating a scientific consensus around anticipated changes in the physical climate system, along with some impacts that are generally implied by those climate changes. The assessments have not characterized or analyzed specific societal risks due to climate change, including socio-environmental causes of vulnerability related to climate hazards.⁵⁴

Commented [MJ6]: To date, the approach of government-sponsored climate change assessments has primarily been rooted in communicating a scientific consensus around anticipated changes in the physical climate system, along with some impacts that are generally implied by those climate changes. Climate assessments have not typically characterized or analyzed specific societal risks resulting from climate change, including the socio-environmental determinants of vulnerability to climate-related hazards.

Climate risk assessments for industry sectors and infrastructure sectors reveal challenges from interconnectivities, interdependencies across value chains, and the impacts of policy and regulations.⁵⁵ International dimensions include mechanisms such as price, material flows, movement of people and political stability, with specific emphasis on food security and geopolitical risks.⁵⁶

The complexity, uncertainty and ambiguity associated with climate risk point to a number of challenges and frontier issues for assessing the risks associated with climate change in a policy-based context. These include the issue of dealing with systemic risks, critical knowledge gaps regarding Earth system processes, and the complexity of societal responses – which could collectively lead to extremely challenging outcomes. Much of the uncertainty in climate change assessments is irreducible; this uncertainty should be treated as a source of actionable knowledge through its influence on the viability of different decision strategies. While the UNFCCC has framed climate risk in terms of dangers, risk assessment should evaluate both positive and negative aspects of change to support a balanced appraisal of alternative decision options. Other issues relate to risk assessment processes themselves, such as managing uncertainty and clarifying the hidden values assumptions of the risk analysts.⁵⁷

This section presents the case that it is time for a shift in the objectives and implementation of climate change assessments – from making what amounts to a general case for ‘action’ regarding eliminating fossil fuel emissions, to characterizing specific regional risks and vulnerabilities in a manner that helps people develop, select, carry out, and monitor actions that ultimately have greater benefits than costs.⁵⁸

10.3.1 How we have mischaracterized climate risk

“The global climate change debate has gone badly wrong. Many mainstream environmentalists are arguing for the wrong actions and for the wrong reasons, and so long as they continue to do so they put all our futures in jeopardy.” – philosopher Thomas Wells⁵⁹

The communication and handling of the climate change risk is strongly dependent on the way risk is conceptualized and described.

In the early 1980’s, the United Nations Environmental Program (UNEP) became bullish on the idea that fossil fuels would produce dangerous climate change. The prospect of eliminating fossil fuels was congruent with UNEP’s broader interests in environmental quality and world governance. At Villach, Austria, in 1985 at the beginning of the climate treaty movement, the policy movement to eliminate fossil fuels became detached from its moorings in the science – the rhetoric of precaution argued that we should act anyway to eliminate fossil fuels, just in case.^{60 61} This perspective became codified by the 1992 UN Framework Convention on Climate Change (UNFCCC) Treaty in 1992, the Kyoto Protocol in 1997 and the 2015 Paris Climate Agreement.

The fundamental presupposition of the UNFCCC climate treaties and agreements is that human-caused climate change associated with fossil fuel emissions is dangerous – natural climate variability and most other human impacts on climate were essentially ignored. There was an implicit assumption that warming was dangerous, ignoring any potential benefits. In attempting to build political will for the international agreements, the adverse impacts of fossil-fuel driven climate change were exaggerated – more frequent and intense severe weather/climate events, sea

level rise and many adverse ecosystem, health, economic and geopolitical impacts, with all of their complex causes, were conflated with fossil-fuel driven warming (Section 1.1).

The torquing of climate science and the manufacture of a consensus around human-caused climate change (Chapter 2) not only oversimplified the scientific and social challenges, but led to the adoption of a “predict then act” strategy to manage and control the climate. This strategy is based on the belief that climate change is a simple or tame problem, with science trumping all practical questions and conflicting values and purposes.

One of the biggest problems associated with climate change assessments is that there is no simple way to articulate danger associated with a warmer climate (Section 1.3). To circumvent this challenge, the problem of climate change has been reduced to one of CO₂ emissions, with the elimination of human-caused emissions as the primary strategy for dealing with the problem. This strategy ignores the fact that there is no precise link between CO₂ emissions and global mean surface temperature, owing to uncertainties in climate sensitivity to CO₂ (Section 7.2) and the poorly constrained natural variations of the climate system. An alternative approach focused on a specified “dangerous” surface temperature threshold.⁶² This approach also requires accurate accounting and projections of natural climate variability from solar variability, volcanic eruptions, and multi-decadal to millennial scale ocean variations (Section 8.2). An additional complication is that the temperature targets of 1.5 and 2.0 °C do not have a sound scientific basis as thresholds for danger (Section 1.3).

Further, the temperature-based approach of specifying a dangerous threshold ignores nonlinearities in the climate system. Climatic “tipping points” (Section 1.3), which have been described as “real critical thresholds,” do not all occur at the same temperature threshold. If

unknown climate tipping points exist that are associated with natural climate processes, there can be no certainty that the risk of climate catastrophe would be eliminated even if emissions fell to zero.⁶³

The end result of the way in which the IPCC/UNFCCC have characterized the climate change problem is that we are focused on meeting emissions targets that are arguably unachievable in the near term, rather than on obtaining a deeper understanding of the climate system and the broader causes of vulnerabilities of human and natural systems. Further, the slow incremental risks of warming have been mischaracterized as urgent, leading to rapid implementation of policies that are not only costly and suboptimal, but also arguably reduce societal resilience to weather and climate variability, whatever their causes.

The politics of international climate governance has produced systematic biases in the kinds of expertise and evidence that are deemed appropriate for consideration.⁶⁴ The UNFCCC and IPCC have characterized climate change as an environmental and economic problem, and geoscientists and economists have dominated the assessment and policy making process.

However, the issues with increasing CO₂ and warming are social, not environmental. The Earth has undergone geological periods of higher temperatures and atmospheric CO₂ concentrations, during which life thrived. Characterization of climate change as an environmental problem has downplayed the cultural and political dimensions of the issue.⁶⁵ In fact, many social scientists have argued that climate change is a values problem, and that the disciplinary constrictions imposed by the IPCC and UNFCCC have neglected many important insights arising from a wide range of expert and unaccredited sources.⁶⁶

Clarifying the multitude of values in play would help illuminate the ambiguity surrounding interpretations of climate risk. However, characterizing climate change as a values problem can also lead into blind alleys. Many environmentalists have moralized the climate change problem as a simple, righteous values choice: Are you for the planet or against it?⁶⁷ This moralizing neglects to understand that people engage in activities which are of value to them that happen to emit carbon as a byproduct.⁶⁸ Further, this narrow moralizing systematically excludes important ethical values, such as improving the lives of the billion people presently living in unacceptable poverty or protecting other aspects of the environment.⁶⁹

The end result is that after 30 years of the UNFCCC/IPCC, we remain fixated on the minutiae of greenhouse gas emissions levels and the abstract and impossible problem of constraining atmospheric CO₂ concentration – while ignoring natural climate variability and drastically simplifying the human impacts and responses. As long as the current situation prevails, the IPCC's assessments of anthropogenic climate change and the UNFCCC recommendations for action will remain seriously inadequate.

This fixation on global CO₂ levels alone as the problem and solution has led Norwegian risk scientist Terje Aven to conclude:

“The current thinking and approaches guiding this conceptualization and description have been shown to lack scientific rigour, the consequence being that climate change risk and uncertainties are poorly presented. The climate change field needs to strengthen its risk science basis, to improve the current situation.”⁷⁰

The UNFCCC is promoting a solution to an exceedingly complex, uncertain and ambiguous problem, without reference to wider ethical issues, and political and practical feasibility. We

have neglected to truly understand the problem and systematically and broadly evaluate the feasible policy space.

10.3.2 Reframing the assessment of climate risk

“[A] problem well put is half solved.” – American philosopher John Dewey⁷¹

Climate risks are exceedingly complex and scientific forecasts are subject to large uncertainties. As a result, there is deep uncertainty within climate change risk assessments. In the face of this deep uncertainty, a conventional predict-then-act approach is paralyzed by limits to prediction and lack of clarity regarding the potential consequences. Estimating the severity of the consequences based only on the potential economic losses ignores a series of impacts that are not easily quantified. In summary, we are far from a thorough assessment of full climate risk that would allow for efficient and targeted policies and support rational risk taking.⁷²

With this context, the risks from climate change need to be reframed more broadly, in context of advances in risk science.⁷³

There is an emerging literature on characterizing systemic risks from climate change. Systemic risks induced by climate change have three basic characteristics: 1) the wide scope of impacts, affecting a wide range of natural, economic and social systems; 2) the long duration of impacts; and 3) cumulativeness of these impacts that grow over time.⁷⁴

Assessment of systemic risk must account for the complexity of the climate system and the integrated effects on politics, the economy, society, culture, and the environment. Both emergency risks associated with extreme weather events and the slow creep of incremental risks have characteristics of systemic risk. Interaction of climate with a variety of processes of global

environmental change (both natural and human systems) represents an increased need to identify and characterize multiple stressors and their interactions across different scales.⁷⁵

How does a categorization of systemic risk actually help with the practical assessment of climate risk? Is such a diagnosis similar to a categorization of a problem as a wicked mess (Section 3.4), which may lead people to throw up their hands and shrug their shoulders? It is sometimes argued that a full assessment of the risks of climate change would be counterproductive, because the risks may be so large and the solutions so difficult that people will be overwhelmed with a feeling of helplessness, and will look the other way. However, rather than stymieing a solution, such categorizations help identify situations where simplistic solutions won't work and suggest paths that may lead to partial solutions and reductions in vulnerability.

There are a number of strategies that can be helpful for assessing systemic risks. These include portraying the full range of extreme future scenarios (global and regional), including extreme weather and climate events and worst-case scenarios (Chapters 8, 9). These scenarios can be used to drive narratives of danger and to stress test social and infrastructure systems. It is important to differentiate between acute impacts associated with extreme weather events versus incremental risks that develop over time, based on different latent periods and manifestations. *Forensic analysis of previous disasters and their complex effects can provide important insights in developing scenarios of systemic risks.*

Judgments of intolerable risks from climate change relate to mistakenly conflating the slow creep of global warming (an emerging risk) with consequences from extreme weather and climate events (emergency risks) and concerns about inequitable risk exposure to poorer populations. Removing the risks associated with the most extreme weather and climate events from the

consequences of global warming diminishes the perceived urgency for reducing fossil fuel emissions. The poorest populations would benefit far more from access to grid electricity and help in reducing vulnerability from extreme weather events, than from reductions to the amount of CO₂ in the atmosphere. Bjorn Lomborg, False Alarm

The uncertainties and complexity of the forces driving the social, biological, and physical dimensions of climate change ensure that we will most likely be surprised by the outcomes. However, there are several features of the climate problem that suggest that climate change related risks will increase in the future. These factors are:⁷⁶

- There is a substantial time lag between the emission of greenhouse gases and the related impacts, and the link to many impacts is not yet fully understood.
- Science is unable to predict long-term impacts accurately enough to provide a strong signpost for action.
- There is large heterogeneity in historical, current and expected future emissions among countries and sectors, and there is no single culprit.
- Variance and heterogeneity of climate related hazards and benefits are large, and winners and losers may change over time.
- There is large heterogeneity in vulnerability among countries, sectors and ecosystems.

The question of intergenerational equity is of special importance for emerging risks, owing to the lag between the emissions of greenhouse gases and the expected occurrence of the damage. There is no simple way to decide what duty of care we owe to future generations, but the IPCC's

socioeconomic pathways for the 21st century all have the world being better off by 2100, even under the most extreme emissions scenarios.

A key to securing meaningful action to reduce climate change risk is to clearly separate the incremental, emerging risks associated with long-term changes in average conditions—which can be addressed to some extent in the long term by reducing greenhouse gas emissions—from the emergency risks associated with extreme weather and climate events, which need to be addressed in both the present and future climate. Any assessment of climate risk needs to approach these two kinds of risk differently, depending on the nature of the decisions it aims to inform.

Once the incremental risks are separated from the emergency risks, the perception of urgency in reducing emissions is diminished. It becomes far more important to develop strategies for managing atmospheric greenhouse gases in a way that supports a transition that does not have adverse impact on security, the economy, industry and agriculture. The challenges for risk assessment are then to identify transition risks associated with proposed solutions to mitigate the rising atmospheric CO₂ content.

At this point, assessing the transition risks of eliminating fossil fuels is arguably more important than attempting to refine our assessments of the deeply uncertain incremental risks associated with fossil fuel emissions. Consequences of the transition are associated with a fairly solid knowledge base, leading many people to be more concerned about transition risks than they are about the more uncertain risks from climate change itself that are associated with a far weaker knowledge base.^{77 78 79}

Assessments of emergency risk associated with extreme weather and climate events generally focus on event type, sectoral impacts or regional assessments. Too many of these assessments are seemingly intended to build political will for eliminating fossil fuel emissions rather than conducting a serious assessment of emergency risk including systemic aspects.

A laudable example of weather emergency risk assessment relates to the ARkStorm scenario described in Section 9.4.2, related to extreme winter flooding in central California.⁸⁰ The state of California's ShakeOut Earthquake Scenario to support preparedness for a major earthquake demonstrated how postulating a hypothetical but plausible catastrophe provides a basis for better examining the interdependencies in social structure and infrastructure and expose choke-points and vulnerabilities.⁸¹ The ARkStorm risk assessment project engaged emergency planners, businesses, universities, government agencies, and others. Following a thorough development of the storm scenario and its direct impacts on inundation and landslides, they assessed secondary impacts on highways, electricity systems, wastewater treatment, water supply, dams, levees, telecommunications, agriculture, buildings, evacuation and sheltering strategies, business interruption, truck transport, and environmental and health issues associated with hazardous materials. The ARkStorm scenario and risk assessment informed community decision-making and is helping communities increase their resilience to severe California winter storms.⁸²

In assessing emergency risk from extreme weather/climate events, there are some key principles to follow:⁸³

1. Emergency risk from extreme weather/climate events is dominated by plausible worst-case events. Looking at extreme event data back to 1950, and calculating return periods, isn't useful here. Global climate models are of no direct use for

extreme event scenarios. Of the three extreme events selected in Section 9.4, the Florida hurricane scenario was based on data from 1935, the ARkStorm scenario was based on data from 1861/62, and the south Asian monsoon failure was based on data from 1756-1768 – the latter two cases were informed not only by historical records but also by paleoclimate reconstructions.

2. Consider all events, even if their probability of occurrence in a particular location is low. The low probability/high impact events, provided that the events are judged to be plausible or have occurred in the past, are associated with the greatest risks. Nevertheless, the cumulative impact of weaker events can also be significant.
3. Be holistic. Account for all relevant factors, as far as possible – including human behavior and the complex interactions between different parts of a system. Evaluate both direct and systemic risks across the relevant time and space windows appropriate to the decision process.]
4. Assess the current risk from weather/climate extremes, based on historical extreme events and today’s societal vulnerabilities. Additional scenarios can be created with incremental effects from global warming.

Commented [MJ7]: Take a holistic view. Account for all relevant factors, as far as possible – including human behavior and the complex interactions between different parts of a system. Assess systemic risks, as well as direct risks. Assess risks across the full range of space and time affected by the relevant decisions.

The seemingly overwhelming challenge of climate risk assessment and the associated political conflicts becomes more tractable by separating the incremental, emerging risk from the emergency risk associated with weather/climate extremes. By regionalizing risk governance, the management approach does not depend on an impossible global agreement for a dubious “perfect” solution that requires moral and political coercion. The regional approach offers a feasible pathway that respects the existing interests and values of the human beings concerned.

This approach works within our existing political institutions (no need for a global government) and offers transparent arguments for action within our present valualational framework, rather than requiring us all to assume a new and narrow set of values.⁸⁴

10.3.3 Climate change versus COVID-19 risk

“There is no power for change greater than a community discovering what it cares about” – writer Margaret Wheatley⁸⁵

The outbreak of the COVID-19 pandemic in the end of 2019 has generated or contributed to a series of interconnected financial, societal, and political crises on a global scale. This has triggered comparative studies of systemic risks of pandemics and climate change, which share many commonalities despite obvious differences.⁸⁶

Both pandemic and climate risks are systemic, in that their impacts propagate rapidly across an interconnected world. Both COVID-19 and climate change risks are nonstationary, with past probabilities and distributions of occurrences rapidly shifting and proving to be inadequate for future projections. Both risks are nonlinear, in that their socioeconomic impact grows disproportionately and even catastrophically once certain thresholds are breached (such as hospital capacity to treat pandemic patients). Both COVID-19 and climate change are risk multipliers, that highlight and exacerbate hitherto untested vulnerabilities inherent in the financial, energy, food and healthcare systems and the overall economy. Both risks affect disproportionately the world’s most vulnerable populations.⁸⁷

However, the timescales of both the occurrence and the resolution of pandemics and climate hazards are different. Pandemic risk is measured in weeks, months, and years; climate risk is

measured in decades and centuries. A pandemic presents imminent, discrete, and directly discernable dangers. By contrast, the risks from climate change, are gradual, cumulative, and distributed, manifesting themselves over time and in spatially heterogeneous way.⁸⁸ The primary difference between the pandemic and climate hazards is that the salience of the threat and perceived urgency of dealing with it.⁸⁹

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1 Carbon dioxide as distinct from criteria air contaminants pollutant

~~This report is chiefly concerned with carbon dioxide (CO₂) emissions from fossil fuel use. In 2007, the Supreme Court ruled that GHGs (CO₂ among them) were “pollutants” subject to regulation under that Clean Air Act. Although it has become common to refer to CO₂ as “pollution” this is a misnomer. In the That framework of United States clean air policy defines there are six types of so-called Criteria Air Contaminants (EPA, undated): particulate matter, ground-level ozone, Sulfur Dioxide, Nitrogen Dioxide, Lead and carbon monoxide (CO). Air contaminants are subject to regulatory control because they cause local problems depending on concentrations that include nuisances (odor, visibility problems), damage to plants and, at high enough exposure levels, toxicological effects in humans.~~

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~~While the definition of “pollutant” is ultimately a legal one, there are important scientific distinctions between CO₂ and the Criteria Air Contaminants—particulate matter, ground-level ozone, Sulfur Dioxide, Nitrogen Dioxide, Lead and carbon monoxide (CO). The latter are subject to regulatory control because they cause local problems depending on concentrations that include nuisances (odor, visibility), damage to plants, and, at high enough exposure levels, toxicological effects in humans. has not historically been viewed as an air pollutant in the US or elsewhere because it is. In contrast, CO₂ is odorless, does not affect visibility and has no toxicological effects at ambient levels. It is a naturally-occurring part of the atmosphere and a key component of human and plant respiration. CO₂ is essential for plant photosynthesis and higher levels are generally considered beneficial for vegetation. In these aspects, it is similar to water, as will be discussed in this report.~~

Commented [SK2]: Whether CO₂ is a pollutant is ultimately a LEGAL question in which we've no particular expertise. There are, however, important scientific aspects to the question where we can credibly opine. I've tried to rewrite to reflect that.

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~~Ambient outdoor air today contains about 420 parts per million (ppm) CO₂, increasing at about 2 ppm per year. The US Occupational Safety and Health Administration issues guidelines for indoor workplaces in which elevated CO₂ may might be encountered, such as where dry ice is used. The Permissible Exposure Limit is 5,000 ppm over 8 hours (OSHA 2024). Allen *et al.* (2015) reported evidence of diminished performance on some cognitive tasks among workers in office cubicles when exposed to CO₂ levels above 1,000-1,500 ppm. These levels are far larger than any plausible ambient outdoor value through the end of the 22nd century.~~

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~~The growing amount of CO₂ in the atmosphere directly influences the earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and also by neutralizing ocean alkalinity. But the primary concern about CO₂ is its role as a greenhouse gas (GHG), that alters the earth's energy balance. How the climate will respond to that influence is a complex question that will occupy much of this report.~~

~~The main concern about CO₂ is its potential effects on the global climate. This is a very complex question which will occupy much of this report. We will begin in the next section by looking at the role of CO₂ in promoting global greening and agricultural productivity growth, then we will examine the effect of CO₂ on ocean alkalinity. We then turn to CO₂'s role as a so-called greenhouse gas (GHG), beginning with a brief description of radiative forcing, the carbon cycle and the role of aerosols. Part II of this report discusses in detail the topic of the climatic response to GHGs. Part III discusses some aspects of the impacts of climate change on ecosystems and society.~~

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Dedining planetary albedo and recent record warmth

Planetary albedo is the fraction of incoming solar radiation that is reflected back into space by the reflective surfaces like cloud tops and snow on the surface and atmosphere, rather than being absorbed at the surface. Earth's planetary albedo is approximately 30%, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed at the surface to be then re-radiated as heat into the atmosphere. Hence, other things being equal, a decline in Earth's albedo is associated with a warming of the atmosphere.

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Arguably the most striking change to the Earth's climate system in the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure xxx shows the planetary albedo variations since 2000, when we have good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m² increase of solar energy averaged over the planet (Hansen and Karecha, 2025). For reference, doubling of CO₂ has a direct radiative impact of about 1.2 W/m².

Looking back prior to 2000 with less adequate data, Gossling et al. (2025) assessed that planetary albedo was relatively low around the 1940's and 50's, before industrial aerosol precursor emissions led to global dimming until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum may have been the lowest since at least 1940.

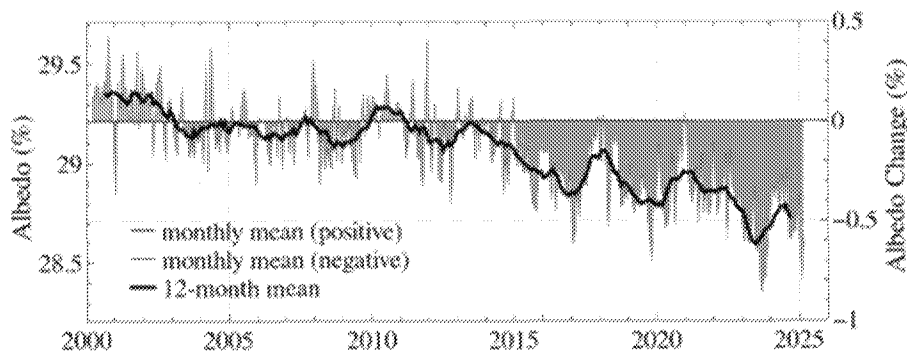


Figure xxx. Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface characteristics can't explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5% since 1980 (https://nsidc.org/data/seaice_index/images/s_plot_hires.png), although following 2007 there has been a pause in the Arctic sea ice decline (England et al, 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that "There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability." (SPM, A.1.5)
- Northern hemispheric snowcover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer.

[[HYPERLINK "http://climate.rutgers.edu/snowcover/"](http://climate.rutgers.edu/snowcover/)]

- Global greening (Chapter 2) is contributing the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo increase associated with increasing forested area.

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

This leaves the most likely explanation for the sharp albedo decline as being caused by changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (e.g. dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall may be producing less dust. In terms of pollution aerosol, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog et al., 2024; Yuan et al., 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

This leaves changes in clouds as the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb et al., 2024; Gosling et al. 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb et al. found that decreases in low and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the northern hemisphere, whereas in the southern hemisphere the decrease in planetary albedo is primarily from decreases in mid-level clouds across all latitude zones. Gosling et al. (2025) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

Two causes have been posited for the declining cloud cover over the past decade:

- Natural climate variability
- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

The existence of a new positive low cloud feedback that began emerging in 2015 is not easy to justify. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was the strongest El Niño event on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic, reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al., 2017; Arthun et al. 2021).

- The Pacific Decadal Oscillation (PDO) positive index peaked in 2016, then declined and has been in negative territory since late 2019
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Interannual cloud anomalies associated with the El Niño Southern Oscillation (ENSO), which have a significant global signal and strong regional signals especially over the tropical Indian and Pacific Oceans

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Gossling et al. (2025) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere, in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarek et al. 2025; Kuchar et al., 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes ~~from direct~~ by couplings between the stratosphere and troposphere. These papers indicate the complex interactions ~~and~~ between volcanic activity and climate dynamics. More research is needed to untangle any impacts of Hunga Tonga eruption on planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1 to 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO₂. While it is difficult to untangle causes of the trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and also the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming, or a temporary fluctuation driven by natural variability

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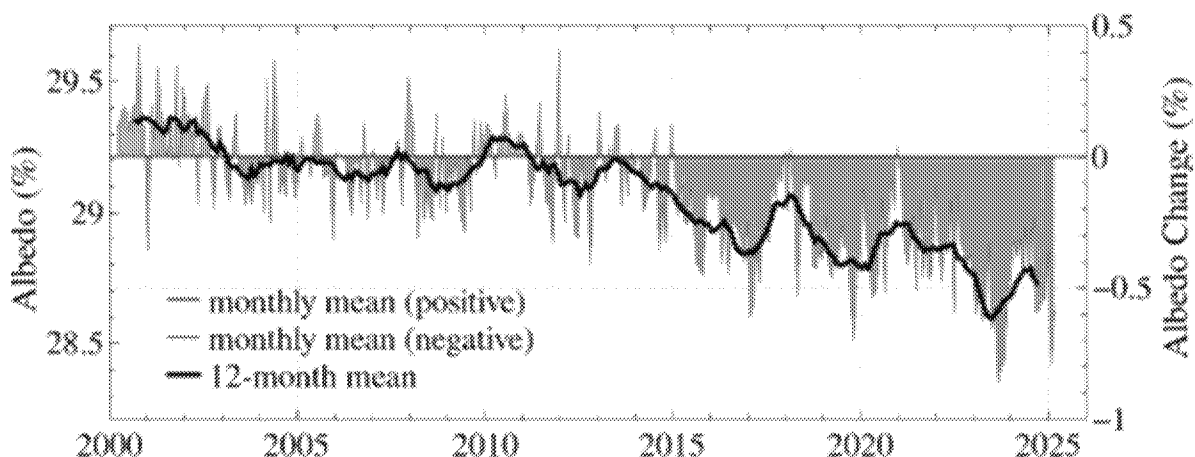


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NS = No Specifics

Is convinced extreme weather is getting worse due to humans. NS

Kudos to CWG. Many comments on earth's climate history. NS

"Appalled". Advises global values of increasing extremes (but did not contradict US extremes)

Water vapor enhancement issues. NS

Suggests Dark Matter (Dark Energy) may be important. NS

Kudos to CWG

Kudos to CWG. Comments on radiation and CO2 v Temp causality

"Cherry-picking, non publishing climate scientists paid by fossil fuel interests", NS

Advises checking US Temperatures for negating CO2 v Temp relationship. NS

Kudos to CWG

GMST is meaningless - ref. C. Essex

PDF document. Complains of process, indicating the Secretary is at fault. NS
Complaints, NS

PDF. Misrepresenting ECS, Solar Variability, extreme events, sea level rise, scenarios, UHI, etc. No counter

Kudos to CWG

Kudos to CWG

Kudos to CWG

Links to reports that scientists claim they were misused in CWG. NS

Very Long, Advises geoengineering. NS

"citations aren't real, clear use of AI". NS

Kudos to CWG

Kudos to CWG

Advise deferring to "Global Expert Consensus" or IPCC. NS

Kudos to CWG

Suspects AI likely did the report. Claims error in citation Lee, S., Byrne, et al 2024. Wrong paper.

Complaints, NS

Kudos to CWG, mitigation must be stopped

Kudos to CWG

Complaints, NS, Christy and Spencer use "fake data"

Complaints, NS

Complaints that extreme weather section is "misleading". Needs "viewpoint diversity". NS

Advises citing statistics for last 20 years on health impacts to capture very recent trends.

"laughable". NS

Claims of extreme weather are "categorically false". CO2 is poisonous. NS

Complaints, NS

"Child's statement of lies." NS

Claims heat mortality section based on old publications. Provides others that say heat mortality is increasing. Kudos to CWG. Notes that Grok's analysis of the report is misleading.

Complaints, NS

Complaints, NS

"Blatently false information". NS

Misleading comments on McKinnons paper, advises stating background is warming in PacNw

Expectant mom wants to save her child from climate change. NS

Complaints, NS

Sec 6.2 - wants slope and p-value for hurricane trends

"foolish and hubristic". NS

^evidence offered.

sing. Sec 10.3

**Factcheck: Trump's climate report includes more than
100 false or misleading claims**

By [[HYPERLINK "https://www.carbonbrief.org/author/ayeshatandon/" \h](https://www.carbonbrief.org/author/ayeshatandon/)], [[HYPERLINK "https://www.carbonbrief.org/author/leohickman/" \h](https://www.carbonbrief.org/author/leohickman/)], [[HYPERLINK "https://www.carbonbrief.org/author/cecilia-keating/" \h](https://www.carbonbrief.org/author/cecilia-keating/)] and [[HYPERLINK "https://www.carbonbrief.org/author/robertmcsweeney/" \h](https://www.carbonbrief.org/author/robertmcsweeney/)] Design by [[HYPERLINK "https://www.carbonbrief.org/author/tomprater/" \h](https://www.carbonbrief.org/author/tomprater/)]

Part I: Direct human influence on ecosystems and the climate

1 Carbon dioxide as a pollutant

Page 2

MISLEADING

The growing amount of CO2 in the atmosphere directly influences the Earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and by neutralising ocean alkalinity.

I see two main problems with this (very old) argument. The direct benefits of CO2 are widely acknowledged and nothing new. But we know that elevated CO2 leads to climate changes and so the question is whether the CO2 benefits are big enough to offset the climate losses. Their report does not address the net effects, which many studies have shown are negative, even for the US. The numbers they cite for direct effects of CO2 are mainly from co2science.org, which is not a reputable source. Their summaries are not peer reviewed and include many studies of pots in greenhouses which are known to be biased. The numbers cited in the report are more than 2x what the best literature shows, such as in Ainsworth & Long (2021).

Part I: Direct human influence on ecosystems and the climate

1 Carbon dioxide as a pollutant

Page 2

MISLEADING

The growing amount of CO2 in the atmosphere directly influences the Earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and by neutralising ocean alkalinity

Anonymous

This ignores other effects of rising CO2 concentrations, i.e.: on climate. It is also failing to mention that increased CO2 can reduce the nutrient density of some crops.

2.1 CO2 as a contributor to global greening

Page 3

FALSE

While plant models predict increased photosynthesis in response to rising CO2, Haverd et al. (2020) reported a CO2 fertilisation rate much larger than model predictions. That is, CO2 fertilisation had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. If true it would indicate that global models of the socioeconomic impacts of rising CO2 have understated the benefits to crops and agriculture.

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/) \h], lead author, IPCC AR6

The paper by Haverd et al. focuses on natural ecosystems, not crops. So whilst the findings that CO₂ fertilisation effects on global greening makes a larger share relative to other factors, the results are not directly transferable to the socio-economic impacts of rising CO₂ on agriculture. Rising CO₂ contributes to higher radiative forcing which increases global mean temperature and accelerates the global water cycle, causing increases in the severity and frequency of extreme weather events (e.g. droughts, heat-stress and wildfires), particularly threatening crop yields and production

2.1 CO₂ as a contributor to global greening

Page 3

MISLEADING

The growing CO₂ concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency.

Anonymous

Promoting plant growth is not always positive, because some species benefit more than others, which creates risks to biodiversity. For example, in tropical forests, elevated CO₂ promotes the growth of lianas, which are parasites that threaten trees. Also increased CO₂ fertilisation is playing a role in disrupting grassland and savannah ecosystems by promoting tree and shrub growth ("woody encroachment").

2.1 CO₂ as a contributor to global greening

Page 3

FALSE

Section 2.1.1

Anonymous

The following section cites papers that are, in fact, showing evidence for other drivers of change, e.g. page 14 line 34 says "Piao et al. (2020) noted that greening was even observable in the Arctic", but Piao et al (2020) actually show that warming is the dominant driver of greening in the Arctic, not CO₂ fertilisation (see figure 4 and associated text). Also the authors of the DoE report contradict their own statement two paragraphs later by saying: "Chen et al. (2019) show that in China and India much of it is driven by land management changes."

2 Direct impacts of CO₂ on the environment

Page 3

MISLEADING

Piao et al. (2020) and Chen et al. (2024) report that the greening trend continues with no evidence of slowdown.

Anonymous

The DoE authors fail to mention another study which shows the opposite, that greening was reversed around the year 2000 over 90% of the global vegetated area.

2.1 CO₂ as a contributor to global greening

Pages 14-17

MISLEADING

Section 2.1

[[HYPERLINK "https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8"](https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8) \h], retired atmospheric physicist

Chapters 2 and 9 assert that CO₂ fertilisation will increase plant growth and crop yields. The proposed benefits of CO₂ fertilisation are not realised in this set of DGVMs because this is only one of several mechanisms that control plant growth. As any farmer knows, plant growth is rarely limited by the abundance of the most abundant nutrient. It is usually limited by the abundance of the least abundant nutrient. While increased CO₂ can accelerate plant growth in carefully controlled laboratory conditions, this rarely happens in nature or in large-scale agriculture. There, plant growth is usually limited by water, nitrogen, phosphorus, sunlight or temperature. These models include all of those effects. The range of outputs produced by the models reflects uncertainties in the relative roles of these processes and their potential evolution with climate change. This behaviour should foster serious concern (doubt) about the potential benefits of CO₂ fertilisation in a changing climate. There is no discussion of this here or in chapters 2.1 or 9.

Quote given to Carbon Brief

2.1 CO₂ as a contributor to global greening

Page 4

MISLEADING

Had atmospheric CO₂ levels continued declining, plant growth would have declined and eventually ceased. Below 180ppm, the growth rates of many C₃ species are reduced 40-60% relative to 350ppm (Gerhart and Ward (2010)) and growth has stopped altogether under experimental conditions of 60-140ppm CO₂. Some C₄ plants are still able to grow at levels even as low as 10ppm, albeit very slowly (Gerhart and Ward (2010)).

[[HYPERLINK "https://case.edu/provost/about/bio"](https://case.edu/provost/about/bio) \h], provost and executive vice president, Case Western Reserve University

"Ward, however, told WIRED in an emailed statement that her experiments were conducted under 'highly controlled growth conditions' to create a 'mechanistic understanding' of CO₂, and that climate change can cause a host of impacts on plants not accounted for in her study. 'With rising CO₂ in natural ecosystems, plants may experience higher heat loads, extreme weather events such as droughts and floods and reduced pollinators — which can have severe net negative effects on plant growth and crop yields,' she says. 'Furthermore, our studies indicate that major disruptions in plant development such as flowering time can occur in direct response to rising CO₂, which were not mentioned in the report.'"

2.1 CO₂ as a contributor to global greening

Page 4

FALSE

Piao et al. (2020) and Chen et al. (2024) report that the greening trend continues with no evidence of slowdown, and CO₂ fertilisation remains the dominant driver.

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/) \h], lead author, IPCC AR6 WG2

Chen et al (2024) does not back up this statement. In the abstract, the author concluded that greening, whilst still increasing, has slowed down: "Our study highlighted that drought trend did not necessarily trigger vegetation browning, but slowed down the rate of greening." Piao et al. (2019) looked at the driver of

global greening. They did not look at whether trends in global greening are rising or decreasing. In addition they analysis focused on historical observation (1980-2010) and did not assess future trends.

2.1 CO₂ as a contributor to global greening

Page 4

MISLEADING

Had atmospheric CO₂ levels continued declining, plant growth would have declined and eventually ceased. Below 180ppm, the growth rates of many C₃ species are reduced 40-60% relative to 350ppm (Gerhart and Ward (2010)) and growth has stopped altogether under experimental conditions of 60-140ppm CO₂. Some C₄ plants are still able to grow at levels even as low as 10ppm, albeit very slowly (Gerhart and Ward (2010)).

Anonymous

The decline in atmospheric CO₂ levels over the last few tens of millions of years stopped naturally, and for the last 800,000 years up until the Industrial Revolution did not show much of a trend, just fluctuating between about 170 and 280 parts per million. The hypothetical scenario of a further decline below these levels is not relevant – it is not the case that human-driven CO₂ emissions have somehow saved us from declining CO₂ levels and declining plant growth, as seems to be the implication behind this paragraph.

2.1 CO₂ as a contributor to global greening

Page 5

MISLEADING

The overwhelming theme is that plants, especially C₃ plants, benefit from extra CO₂.

Anonymous

While individual plants benefit in isolation, the overall effect on an ecosystem and biodiversity can be detrimental due to some species benefitting more than others and out-competing them – for example, lianas responding more than trees, which they damage, encroachment of trees and shrubs into grasslands and savannahs, and the promotion of invasive species and weeds.

2.1 CO₂ as a contributor to global greening

Page 5

MISLEADING

There are two mechanisms by which CO₂ confers a growth benefit

A "growth benefit" to the plant is not necessarily beneficial in other ways – for example, from IPCC AR6: "Perennial crops and root crops may have a greater capacity for enhanced biomass under elevated CO₂ concentrations, although this does not always result in higher yields. For some food crops, nutrient density declines due to elevated CO₂." And: "Elevated CO₂ reduces some important nutrients such as protein, iron, zinc and some grains, fruit or vegetables to varying degrees depending on crop species and cultivars."

2.1 CO₂ as a contributor to global greening

Page 5

MISLEADING

The gains induced by increasing CO₂ from 150ppm to 350ppm continue under a further doubling to 700ppm.

Anonymous

This very simplistic illustration from a small laboratory study ignores key effects such as nutrient availability, which in the real world can constrain the response to elevated CO₂.

Quote given to Carbon Brief

Supporting evidence

[[HYPERLINK "https://onlinelibrary.wiley.com/doi/10.1111/gcb.16377" \h](https://onlinelibrary.wiley.com/doi/10.1111/gcb.16377)]

2.2 The alkaline oceans

Pages 17-18

MISLEADING

Section 2.2.1

[[HYPERLINK "https://wmo.int/profile/john-kennedy" \h](https://wmo.int/profile/john-kennedy)], climate scientist

"The first subsection builds towards the conclusion in the summary that 'ocean life is complex and much of it evolved when the oceans were acidic relative to the present'. Leaving aside the vacuity of this argument for the moment – life itself evolved when there was little oxygen in the atmosphere, the biochemical innovations that flooded the atmosphere with oxygen were catastrophic for life then, but see how we would do without it now – their citations are spare and strange particularly within the context of later arguments about the value of models and the contention that this is some sort of meaningful 'critical review'. The first paper they cite regarding long-term change in ocean pH is Krissansen-

Totton et al. (2018), which uses a model to constrain climate and ocean pH of the early Earth up to the

present. They find that ocean pH evolves monotonically from 6.6 (see the abstract of the paper for the broad uncertainty ranges) at 4.0 Ga to 7.0 at the Archean-Proterozoic boundary, and to 7.9 at the Proterozoic-Phanerozoic boundary reaching a modern value of 8.2. While we might raise an eyebrow that the 'critical review' finds models are good enough for the herculean task of reproducing almost the whole of Earth's climate history, but not for understanding the past 200 years, the eyebrow is likely to go shooting off your face when you reach the sentence in the 'critical review' that says: 'Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0.' I derive little comfort from the fact that simple life forms evolved in such conditions. The gist of the 'critical review' isn't that simple life forms will survive the current warming, but that human society supported by a flourishing biosphere will not just survive but thrive. Anyway, this is only part of an argument and the whole of the argument is never really spelled out. It seems to go something like this: pH of the ocean varied in the past and we exist today, therefore we will always exist and pH of the ocean is unimportant.

"The second, shorter, long-term perspective, which feeds into this argument, mixes up surface pH (as shown in Figure 2.3 from the CMEMS dataset) with deep ocean pH (from Rac et al. (2018)) who (according to their abstract) 'present deep-sea coral boron isotope data that track the pH – and thus the CO₂ chemistry – of the deep Southern Ocean over the past forty thousand years'. 'Deep' and 'track' are the operative words here. The estimated changes are 'deep', from a depth of around 750 metres and not the surface. Regarding 'track', the numbers quoted in the 'critical review' – pH of 7.4 to 7.5 20,000 years ago – came presumably from Figure S1 in the Rac paper, which provides an approximate conversion of the boron isotopes to pH. How very very approximate they are is shown by an inset uncertainty range, which extends from well below 7.4 to well above 7.6 suggesting great care is needed in the interpretation of the absolute pH values."

Quote from [[HYPERLINK "https://diagrammonkey.wordpress.com/2023/04/20/if-a-komodo-dragon-bites-john-then/"](https://diagrammonkey.wordpress.com/2023/04/20/if-a-komodo-dragon-bites-john-then/)] \h]

2.2 The alkaline oceans

Pages 18-19

MISLEADING

Section 2.2.2

[[HYPERLINK "https://wmo.int/profile/john-kennedy/"](https://wmo.int/profile/john-kennedy/)] \h], climate scientist

"The first two paragraphs of the 'critical review' are on that famous American landmark the Great Barrier Reef. And why not? Well. One 'why not' can be found in the IPCC report (AR6 WG2). Chapter 11 has a box ('Box 11.2 | The Great Barrier Reef in Crisis'). It doesn't mention ocean acidification as a risk to the GBR at all (though OA is mentioned frequently elsewhere). The two big risks mentioned are bleaching in response to marine heatwaves and erosion caused by tropical cyclones. Neither of these factors is unconnected to climate change. Ocean acidification may not be a risk to the GBR, but climate change certainly is. The AIMS website which is referenced in the 'critical review' even notes 'a high tolerance in massive Porites to ocean acidification'. The GBR is introduced here as a 2,300km long straw man.

"The rest of the section concerns itself with the more general impacts of ocean acidification. But only glancingly. They cite Browman (2016) on the lack of null results in the literature and offer, as an example, Clements et al. (2021) which is about the direct effects of OA on the behaviour of fish specifically (not the reefs themselves) though it does have a juicy metascientific quote that serves their purpose of suggesting that

discussion of the topic is one-sided. If anything, Clements et al. shows that the literature is no longer one-sided so it rather weakens the point they are trying to make...The Browman article is also somewhat meta and points out that papers on ocean acidification were appearing at an average rate of 300 per year between 2006 and 2015, with around 600 articles per year in each of 2013, 2014 and 2015. How many are there now? I don't know. The Browman and Clements articles are both old-as in the context of a fast-moving field. A simple Google Scholar search will show you that not only are there huge numbers of papers mentioning the topic in the past five years, but there are even lots of review papers and meta analyses on the topic which cover a much broader range of impacts. Summarising that literature with just 12 references (including links to the data used) is not adequate by any definition."

2.1 CO₂ as a contributor to global greening

Page 6

MISLEADING

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO₂ both to enhance photosynthesis and to reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO₂ Enrichment – see Chapter 9) on crop yield changes for maize (corn), wheat, rice, and soybean and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 emissions scenario in four growing regions (tropics, arid, temperate and cold) each of which were split into rainfed and irrigated sub-regions. They reported that models without CO₂ fertilisation predicted CWP losses in every region, but those were more than offset by CO₂ fertilisation so that all regions showed a net CWP gain. Deryng et al. (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90% for rice and 60% for maize.

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/)
\h], lead author, IPCC AR6 WG2

While those are general conclusions of the paper, they are misleading by not mentioning the considerable discrepancy among modelled results. In fact, this paper was the first of its kind to present findings from the first global modelling intercomparison initiative of global gridded crop models, focusing specifically on how state-of-the-art models represented CO₂ effects on crop yield and evapotranspiration, highlighting these effects as a dominant source of uncertainty in the results, outpassing the uncertainty resulting from the use of different climate change projections. The supplementary information of the paper includes the detailed uncertainty analysis. A key message of the paper was also to highlight the needs for further research on the effects of CO₂ on crops and their representation in crop models. Toreti et al. (2020) provides a comprehensive review of the uncertainties associated with the effects of elevated CO₂ on crops,

2.1 CO₂ as a contributor to global greening

Page 6

FALSE

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. Yet while models do predict that drylands will expand under climate warming, current data show the opposite:

greening is happening even in arid areas.

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/) \h], lead author, IPCC AR6 WG2

Greening and water scarcity are processes related to different carbon and water cycles, respectively. They cannot be directly compared. Deryng et al. (2016) didn't assume but reported findings from peer-reviewed scientific studies on water scarcity trends. Deryng et al (2016) specifically stated: "Research indicates unabated climate change will exacerbate water scarcity around the world. This is thought to threaten agricultural productivity and food security, especially in arid regions, where agriculture relies heavily on irrigation and consumes the majority of diverted freshwater."

2.1 CO₂ as a contributor to global greening

Page 6

FALSE

The IPCC has only minimally discussed global greening and CO₂ fertilisation of agricultural crops. The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier assessment reports but is omitted in all summary documents. Section 2.3.4.3.3 of the AR6 WG1 report, entitled "global greening and browning," points out that the IPCC special report on climate change and land had concluded with high confidence that greening had increased globally over the past two-to-three decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have high confidence greening has occurred, they have low confidence in the magnitude of the trend. There are also brief mentions of CO₂fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 WG1 and 2 reports.

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/) \h], lead author, IPCC AR6 WG2

Chapter 5 of IPCC WG2 AR6 has reported the state of knowledge of CO₂ fertilisation effects on crops, including photosynthesis stimulation, evapotranspiration reductions, as well as elevated CO₂ effects on the quality of crops. These are widely discussed throughout the chapter, including in figures 5.6, 5.7, and 5.11, as well as in sections 5.2.1 (Detection and Attribution of Observed Impacts), 5.4.1 (Observed Impacts of crop-based systems), 5.4.3 (Projected Impacts of crop-based systems), 5.4.4 (Adaptation Options of crop-based systems), 5.5.3 (Projected Impacts of Livestock-Based Systems), 5.6.2 (Projected Impacts of forestry systems), 5.10.3 (Projected Impacts of mixed systems), 5.12.2 (Mechanisms for Climate Change Impacts on Food Security), 5.12.4 (Projected Impacts on Food Security). The effects of elevated CO₂ on food systems are also included in the summary tables 5.9 (Observed and predicted impacts of climate change on selected medicinal plant species) and 5.14 (Impacts from climate change drivers on the four dimensions of food security).

2.1 CO₂ as a contributor to global greening

Overall, however, the policymaker summaries, technical summaries and synthesis reports of AR5 and AR6 do not discuss the topic.

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/)
\h], lead author, IPCC AR6 WG2

The technical summary does include a statement of CO2 fertilisation effects on vegetation and crops. Specifically in the observed and projected impacts sections (TS.B.1.5 and TS.C.1.4) as well as in Figure TS.6 FOOD-WATER. The summary for policymakers includes a summary of the findings. In the case of agriculture the overall key risks are reported, which are based on the overall assessment of observed and projected impacts of climate change, including effects of CO2 fertilisation, as well as potential contribution of adaptation measures on global and regional food production and food security.

2.1 CO2 as a contributor to global greening

Page 6

MISLEADING

The IPCC has only minimally discussed global greening and CO2 fertilisation of agricultural crops.

Anonymous

The IPCC has extensively discussed the promotion of plant growth by rising atmospheric CO2 concentrations and consequent effects on global vegetation and land carbon sinks, including in summary documents — just not using the specific term "global greening" since other terms are used. The AR6 WG1 carbon cycle chapter prominently discusses the uptake of carbon in land ecosystems, e.g. in the executive summary page ("The ocean and land sinks of CO2 have continued to grow over the past six decades in response to increasing anthropogenic CO2 emissions (high confidence)") and in Frequently Asked Question 5.1. The WG1 summary for policymakers includes a figure showing the land carbon sink (Figure SPM.7). In WG2, chapter 2 on terrestrial ecosystems also discusses this, e.g. in the executive summary: "Biome shifts and structural changes within ecosystems have been detected at an increasing number of locations, consistent with climate change and increasing atmospheric CO2 (high confidence)" and "A combination of changes in grazing, browsing, fire, climate and atmospheric CO2 is leading to observed woody encroachment into grasslands and savannah."

The WG2 technical summary includes a figure showing woody encroachment (Figure TS12) and the WG2 summary for policymakers states that "at the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere than they emit", but also notes: "However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources." (page 20 footnote 39). The WG2 food chapter extensively discusses effects of elevated CO2 on crops, including both past and projected future changes. The summary documents focus on overall outcomes from the combined effects of climate change, elevated CO2 and other changes in atmospheric composition. The IPCC also specifically notes that elevated CO2 can reduce nutritional quality in crops.

2.1 CO2 as a contributor to global greening

Page 6

FALSE

The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier assessment reports.

Anonymous

The topic of CO2 fertilisation effects, including their limitations and interactions with other drivers of change, are extensively discussed in AR6 WG2 chapter 5 (Food, Fibre and Other Ecosystem Products). The term "CO2" appears 136 times in that chapter. In the WG1 report, Chapter 5 is "Global Carbon and Other Biogeochemical Cycles and Feedbacks" and, again, extensively includes discussion of CO2 effects as part of the carbon cycle.

2.1 CO2 as a contributor to global greening

Page 6

FALSE

Overall, however, the policymaker summaries, technical summaries and synthesis reports of AR5 and AR6 do not discuss the topic.

Anonymous

The WG1 summary for policymakers includes a figure showing the land carbon sink (Figure SPM.7) and the caption includes: "Land and ocean carbon sinks respond to past, current and future emissions...During the historical period (1850-2019) the observed land and ocean sink took up 1430 GtCO2 (59% of the emissions)." The WG2 technical summary includes a figure showing woody encroachment (Figure TS12) and the WG2 summary for policymakers states: "At the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere than they emit." It also notes: "However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources." In AR5, the WG1 SPM says: "Of these cumulative anthropogenic CO2 emissions...160 [70 to 250] GtC have accumulated in natural terrestrial ecosystems (i.e., the cumulative residual land sink)."

2.2 The alkaline oceans

Page 7

MISLEADING

Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0 (Krissansen-Totton et al. (2018)).

[[HYPERLINK](https://depts.washington.edu/astrobio/wordpress/profile/joshua-krissansen-totton/)

"<https://depts.washington.edu/astrobio/wordpress/profile/joshua-krissansen-totton/>" \h], assistant professor, Earth and space sciences , University of Washington

‘Krissansen-Totton told WIRED in an email that his work on ocean acidity billions of years ago has ‘no relevance’ to the impacts of human-driven ocean acidification today and that today calcium carbonate saturation is quickly diminishing in the ocean alongside rising acidity. Dissolved calcium carbonate is essential for many marine species, particularly those that rely on it to build their shells.’ The much more gradual changes in ocean pH we observe on geologic timescales were typically not accompanied by the rapid changes in carbonate saturation that human CO₂ emissions are causing, and so the former are not useful analogs for assessing the impact of ocean acidification on the modern marine biosphere,’ he says.”

2.2 The alkaline oceans

Page 7

MISLEADING

Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0 (Krissansen- Totton et al. (2018).

[[HYPERLINK "https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/"](https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/) \h], reader, geochemistry and climate, University of St Andrews

Modern marine life and ecosystems (e.g. coral reefs and open ocean fisheries) are very different from the initial lifeforms that evolved in the earliest oceans (e.g. bacteria, single-celled organisms) and so have different adaptive ranges and vulnerabilities. In the same way that the environmental conditions which were suitable for dinosaurs have little relevance for optimal conditions for humans, there is little relevance in comparing early ocean bacterial habitats to the conditions to which modern marine life has adapted.

2.2 The alkaline oceans

Page 7

MISLEADING

On the time scale of thousands of years, boron isotope proxy measurements show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al. (2018)).

[[HYPERLINK "https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/"](https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/) \h], reader, geochemistry and climate, University of St Andrews

The use of "ocean pH" in this statement is misleading, as it seems to imply whole ocean pH or (following

from the text above) the pH of the surface ocean, whereas the boron isotope study referenced here (of which I was the first author) apply only to the deep Southern Ocean. These are completely different habitats occupied by completely different species. The habitats of most concern with respect to ocean acidification are in the surface (e.g. coral reefs, key fisheries), where pH was higher than today during the last ice age (e.g. Shao et al., 2019), not lower as suggested in figure 5 of Shao et al. (2019).

Quote given to Carbon Brief

2.2 The alkaline oceans

Page 7

MISLEADING

Thus, ocean biota appear to be resilient to natural long-term changes in ocean pH since marine organisms were exposed to wide ranges in pH.

[[HYPERLINK "https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/" \h](https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/)], reader, geochemistry and climate, University of St Andrews

Natural long-term changes in ocean pH have a fundamentally different impact on ocean chemistry than rapid input of carbon from fossil fuels (see Honisch et al. (2011)). When ocean pH is lowered rapidly (e.g. on decadal to centennial timescales), the abundance of carbonate ions decreases rapidly. As these carbonate ions are the most critical ingredient for marine shell formation, shells become harder to grow. Technically, this is known as a drop in calcium carbonate saturation state and it makes calcium carbonate shell formation more energetically costly (e.g. Gagnon et al., (2021)). In contrast, when ocean pH is lowered slowly (e.g. on timescales of a thousand years or more), the dissolution of seafloor calcium carbonate, alongside weathering of rocks on land, has a buffering effect on ocean saturation state, allowing shell formation to continue unimpeded despite the lower pH. Today, anthropogenic CO₂ emission is lowering ocean pH on decadal to centennial timescales, which are too rapid for these buffering processes to keep up with, resulting in lower calcium carbonate saturation states, and making shell formation more energetically costly and enhancing environmental stress on these organisms.

2.2 The alkaline oceans

Page 8

MISLEADING

Similarly, a meta-analysis (Clements et al. (2021)) of the negative effects of ocean acidification on reef fish behavior found what they called a “decline effect”: initially dramatic conclusions published in prominent journals showing apparently large impacts of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to counter the “decline effect”: [The] vast majority of studies with large effect sizes in this field tend to be characterised by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behaviour, and we advocate for improved approaches to minimise the potential for a decline effect in future avenues of research (Clements et al. (2021)).

[[HYPERLINK "https://jclementsphd.ca/" \h](https://jclementsphd.ca/)], marine ecologist, Fisheries and Oceans Canada (Gulf Region)

“Clements...says that the way the DoE report cites his research on ocean acidification and fish behavior is accurate ‘from an explicit textual perspective’...Clements says in an email to WIRED that just because his review of the literature found fish behavior to be relatively unaffected by ocean acidification does not mean that a myriad of other ocean ecosystems, biological processes and species will fare similarly. Other work from his lab, meanwhile, has underscored the vulnerability of mussels to ocean warming and looked at how heat waves negatively alter clam behavior...‘I want to make it clear that our results should not be interpreted to mean ocean acidification (or climate change more generally) is not a problem,’ he tells WIRED. ‘While effects on fish behavior may not be as severe as initially thought, other species and biological processes are certainly vulnerable to the impacts of acidification and the compendium of other climate change stressors that our oceans are experiencing.’”

2.2 The alkaline oceans

Page 8

MISLEADING

Similarly, a meta-analysis (Clements et al. (2021)) of the negative effects of ocean acidification on reef fish behaviour found what they called a “decline effect”: initially dramatic conclusions published in prominent journals showing apparently large impacts of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects.

[[HYPERLINK "https://www.ntnu.edu/employees/fredrik.jutfelt" \h](https://www.ntnu.edu/employees/fredrik.jutfelt)], professor of fish ecophysiology, Norwegian University of Science and Technology

The way the DoE report cites our own work is flawed, as they use a specific finding in a small subsection of the field to represent the state of the entire field. This is intellectually dishonest and unscientific, and suggests either gross incompetence or an underlying bias.

Quote given to Carbon Brief

2.2 The alkaline oceans

Page 8

MISLEADING

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. The ancestors of modern coral first appeared about 245m years ago. CO2 levels for more than 200m years afterward were many times higher than they are today. Much of the public

discussion of the effects of ocean "acidification" on marine biota has been one-sided and exaggerated.

[[HYPERLINK "https://wmo.int/profile/john-kennedy"](https://wmo.int/profile/john-kennedy) \h], climate scientist

The factoid about coral appearing 245m years ago is unreferenced and not previously mentioned in the section. The contention regarding 'much of the public discussion' is likewise unreferenced and not mentioned elsewhere in the section. Public discussion and scientific discussion are two different things.

Public discussion isn't discussed at all and, anyway, the 'critical review' is supposedly reviewing the science.

I think it's safe to say it has failed there too. Quote from [[HYPERLINK](https://diagrammonkey.wordpress.com/2023/04/20/if-a-komodo-dragon-bites-john-then/)

"<https://diagrammonkey.wordpress.com/2023/04/20/if-a-komodo-dragon-bites-john-then/>" \h]

2.2 The alkaline oceans

Page 8

MISLEADING

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. The ancestors of modern coral first appeared about 245m years ago. CO2 levels for more than 200m years afterward were many times higher than they are today. Much of the public discussion of the effects of ocean "acidification" on marine biota has been one-sided and exaggerated.

[[HYPERLINK "https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/" \h](https://www.st-andrews.ac.uk/earth-sciences/people/jwbr/)],
reader, geochemistry and climate, University of St Andrews

As discussed above, long-term geological pH changes are not a good analogue for a rapid drop in pH of the type happening today, for the key reason that a rapid pH drop results in lowered calcium carbonate saturation state, which makes shell formation harder (e.g. Honisch et al., (2011)). To find better analogues for modern pH decline in the geological record, we need to look at times when ocean pH dropped more quickly. Data of this type are compiled in a recent study by Trudgill et al. (2025). These show that all of the major mass extinction events in the ocean for which we have pH reconstructions are associated with a rapid drop in ocean pH. The geological record thus suggests that rapid pH decline is a matter for serious concern for marine ecosystems and the communities and economies which they support.

Quote given to Carbon Brief

Supporting evidence

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References

Page 9

FALSE

Chen, X., Wang, Y., Liu, Y., and Piao, S. (2024). The global greening continues despite increased drought stress since 2000. Global Ecology and Conservation, 49, e02791.

Anonymous

The author list is incorrect on this citation. It should be Xin Chen, Tiexi Chen, Bin He, Shuci Liu, Shengjie Zhou and Tingting Shi. It falsely associates the paper with well-known authors and demonstrates lack of attention to detail.

3 Human influences on the climate

Page 11

MISLEADING

The IPCC has downplayed the role of the sun in climate change, but there are plausible solar irradiance reconstructions that imply it contributed to recent warming.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27569"](https://www.mps.mpg.de/solar-physics/staff/27569) \h],
astrophysicist, Max Planck Institute for Solar System Research

This is a vague and potentially misleading statement. The IPCC AR6 adopted the solar radiative forcing values recommended by CMIP6, while AR5 used those from CMIP5. In both cases, the TSI [total solar irradiance] reconstructions selected were the most advanced and extensively scrutinised available at the time (Matthes et al. (2017)). The notion that there exist "plausible" solar irradiance reconstructions implying a solar contribution to recent warming is misleading, since it leaves it vague as to how much it contributed. The most scientifically robust irradiance reconstructions indicate that this contribution has been relatively small in recent decades. The wording of this statement appears to implicitly reference the work of Connolly et al. (2021) and (2023), although only the former is cited in the DoE report. Connolly et al. (2021) argued that a significant portion, or even most, of recent global warming could be attributed to solar variability. However, their approach involved cherry-picking and balancing 16 TSI reconstructions: eight with low long-term variability and eight with high variability. To create this balance, they included outdated or superseded models while omitting many low-variability reconstructions.

The high-variability series used by Connolly et al. (2021):

- Hoyt and Schatten (1993) has been thoroughly discredited (see Chatzistergos (2024)). It includes arbitrary manual adjustments and even fabricated data, with some values seemingly copied from another solar index.

- Lean et al. (1995) is an early version of the NRL [Naval Research Laboratory] model that has since been superseded by multiple updated versions, most recently NRLTSI2/NNL (Coddington et al. (2016) and (2019)).
 - Bard et al. (2000) used a simplified linear conversion from cosmogenic isotope production (e.g., ^{10}Be) to TSI, without accounting for nonlinear effects such as geomagnetic modulation, atmospheric transport processes, or climate-driven deposition variations. These omissions have been addressed in more physically realistic models like SATIRE-M [Spectral And Total Irradiance REconstructions] (Wu et al. (2018)), which show significantly lower long-term variability.
- Furthermore, Delaygue and Bard (2011) revised the original Bard et al. (2000) reconstruction which was exhibiting low long-term variability, yet this update was ignored by Connolly et al. (2021).
- Shapiro et al. (2011), an older high-variability model, was effectively replaced by Egorova et al. (2018), which itself has been criticised by Yeo et al. (2020) for exaggerating long-term TSI changes. - Egorova et al. (2018) was included four times in the Connolly et al. (2021) analysis. Including Shapiro et al. (2011), a predecessor of Egorova's model, the same model family was effectively used five times, artificially inflating the weight of high-variability reconstructions.

Crucially, in all these high-variability models, the long-term TSI trends were not derived from observational constraints but were imposed as assumptions. Modern revisions of the NRL model (Lean (2018) and Coddington et al. (2019)) and the Hoyt and Schatten model (Chatzistergos (2024)) have significantly reduced these assumed trends to align with observational evidence. Therefore, treating these outdated, superseded, or methodologically flawed reconstructions as equally probable alternatives to modern, validated TSI models is scientifically unjustified. It creates a false equivalence that misrepresents the current state of solar irradiance research. Connolly et al. (2023), although not cited in the DoE report, extended the analysis to 27 TSI series. However, the same methodological issues persist. Many of the added reconstructions are either outdated or redundant versions of older models.

Notably, the highest solar attribution results again stem from Hoyt and Schatten (1993) and Bard et al. (2000), both of which have been superseded and shown to be unreliable. Finally, the attribution method used by Connolly et al. (2021) was directly critiqued by Richardson and Benestad (2022), who identified substantial flaws in their regression methodology and treatment of uncertainty. Even with the analysis presented in Connolly et al. (2021) and (2023) when the outdated, superseded and implausible TSI series are removed, the result is that the solar contribution to global warming is significantly smaller than the anthropogenic one.

3.1 Components of radiative forcing and their history

Page 12

MISLEADING

The IPCC assesses the change in the radiative forcing by the sun to be negligible, based on their preference for data reconstructions that imply minimal solar change since pre-industrial times.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27568"](https://www.mps.mpg.de/solar-physics/staff/27568) \h],
astrophysicist, Max Planck Institute for Solar System Research

The selection of TSI reconstructions for use in CMIP6 and IPCC AR6 was based on the scientific robustness and performance of the models, rather than the magnitude of TSI variability they imply (Matthes et al.

(2017)). The two reconstructions adopted were SATIRE and NRLTSI (now referred to as NNLTSI). These models were chosen because they represent the most advanced TSI reconstructions currently available. SATIRE is a semi-empirical, physics-based model, while NNLTSI is a proxy-based regression model. Both have been extensively validated and demonstrate excellent agreement with direct satellite measurements of TSI, making them the most reliable choices for climate modeling to date.

3.1 Components of radiative forcing and their history

Page 12

MISLEADING

But Connolly et al. (2021) reviewed 16 different Total Solar Irradiance (TSI) reconstructions in the literature covering the years 1600-2000; the reconstructions vary from almost no change in TSI to a relatively large upward trend. Those authors note that the variation in TSI reconstructions combined with variations in surface temperature reconstructions allows for inferences consistent with either no or most 20th century warming being attributable to the sun.

Dr Theodosius Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research

The approach by Connolly et al. (2021) involved cherry-picking and balancing 16 TSI reconstructions: eight with low long-term variability and eight with high variability. To create this balance, they included outdated or superseded models while omitting many low-variability reconstructions.

The high-variability series used by Connolly et al. (2021):

- Hoyt and Schatten (1993) has been thoroughly discredited (see Chatzistergos (2024)). It includes arbitrary manual adjustments and even fabricated data, with some values seemingly copied from another solar index.

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Crucially, in all these high-variability models, the long-term TSI trends were not derived from observational constraints but were imposed as assumptions. Modern revisions of the NRL model (Lean (2018) and Coddington et al. (2019)) and the Hoyt and Schatten model (Chatzistergos (2024)) have significantly reduced these assumed trends to align with observational evidence. Therefore, treating these outdated, superseded, or methodologically flawed reconstructions as equally probable alternatives to modern, validated TSI models is

scientifically unjustified. It creates a false equivalence that misrepresents the current state of solar irradiance research.

3.1 Components of radiative forcing and their history

Page 13

MISLEADING

A particularly thorny issue is the gap in TSI data between 1989 and 1991 due to a delay in the launch of a monitor following the Space Shuttle Challenger

” [A gap in TSI measurements between the ACRIM-1 and ACRIM-2 satellite monitoring experiments] as a "particularly thorny" issue. While it does contribute to uncertainty in the long-term trend of direct TSI measurements, a growing body of evidence challenges the notion of a TSI increase during the ACRIM-gap, evidence which the DoE report entirely overlooks. Notable examples include Amdur & Huybers (2023), Chatzistergos et al. (2025) and Krivova et al. (2009).

Quote given to Carbon Brief

3.1 Components of radiative forcing and their history

Page 13

FALSE

Connolly et al. (2021) found that the IPCC's consensus statements on solar forcing were formulated prematurely through the suppression of dissenting scientific opinions.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27559"](https://www.mps.mpg.de/solar-physics/staff/27559) \h],
astrophysicist, Max Planck Institute for Solar System Research

This is yet another statement in the DoE report that is vague. It is not clear what they refer to with consensus, is this about the long-term reconstructions, is it just about the ACRIM-gap that this paragraph discusses? In any case, it appears as a general statement which as such has to be labelled as false. The claim that dissenting scientific opinions are being suppressed is unfounded.

Scientific consensus evolves through rigorous evaluation, not censorship. When significant methodological issues are identified, such as the arbitrary adjustments and fabricated data in the Hoyt and Schatten (1993) TSI reconstruction (Chatzistergos (2024)), it is scientifically appropriate to disregard such models as implausible. This is not suppression of dissenting voices, but the enforcement of standards for methodological soundness.

Another example is the Bard et al. (2000) TSI reconstruction, which has since been superseded by more advanced models. Bard et al. (2000) relied on a simplistic linear scaling of cosmogenic isotope production to estimate TSI variability, without accounting for the non-linear influence of geomagnetic field modulation on isotope production. This omission leads to inaccurate estimates of solar variability. Later reconstructions, such as those based on the SATIRE-M framework (e.g., Wu et al. (2018)), incorporate these critical non-linearities and have been shown to produce more consistent results with observational constraints. Albeit, uncertainties remain and more work is being invested in improving these reconstructions too. Furthermore, we have advanced physics-based irradiance reconstruction models, e.g. SATIRE-3D (Yeo et al. (2017) and

(2020), which have been used to set robust constraints on the magnitude of plausible TSI variations. As a result, irradiance reconstructions that exceed this constraint are considered less plausible than those that remain within it. Disregarding outdated or methodologically flawed reconstructions is a hallmark of scientific integrity, not suppression. The continued use of discredited models undermines robust scientific discourse and misrepresents the state of knowledge. A reminder here that the study by Connolly et al. (2021) cherry-picked 16 TSI reconstructions, deliberately balancing the sample by including eight with small long-term trends and eight with pronounced trends. The high-variation models they used are Hoyt and Schatten (1993), Lean (1995), Bard et al. (2000), Shapiro et al. (2011) and Egorova et al. (2018; used 4 different versions). Besides the issues with Hoyt and Schatten (1993) and Bard et al. (2000) discussed above, Lean (1995) is an outdated precursor to the NRL (now NNL) model and is no longer considered plausible. Shapiro et al. (2011) and Egorova et al. (2018) are different versions of the same model both exceeding the Yeo et al. 2020 constraint.

3.1 Components of radiative forcing and their history

Pages 22-24

MISLEADING

Section 3.1.1

[[HYPERLINK "https://schoeberl.academia.edu/"](https://schoeberl.academia.edu/) \h], chief scientist, Science and Technology Corp

The paper by Jenkins et al. (2023) did not include volcanic aerosol effects and thus estimated the wrong sign of the Hunga volcano radiative forcing.

Subsequent papers (including my own) agree that Hunga would produce slight cooling. The inclusion of the Jenkins paper here suggests more uncertainty in the calculation than exists. All models and data analyses agree that Jenkins was incorrect (e.g. Stenchikov et al. (2025) and Zhuo et al. (2025)).

3.2 Future emission scenarios and the carbon cycle

Page 15

FALSE

Comparisons of past scenario groups against observations show that IPCC emission projections have tended to overstate actual subsequent emissions. For the IPCC third and fourth Assessment Reports a set of emission projections from the special report on emission scenarios was used; these were referred to as the SRES scenarios. McKittrick et al. (2012) showed that, when converted to per capita values, the SRES scenario emissions distribution was skewed upwards compared with observed trends.

[[HYPERLINK "https://berkeleyearth.org/team/"](https://berkeleyearth.org/team/) \l "zeke-hausfather" \h], research scientist, Berkeley Earth

While some past IPCC emissions scenarios have overstated future total CO₂ emissions (IS92B, A1F1, RCP8.5), others have understated them (IS92D, B2, RCP6). In general total CO₂ emissions were on the high

end of the range of both the 1992 IS92 scenarios and the 2000 SRES scenarios through 2015, before falling closer to the middle of the range in recent years. Notably both IS92 and SRES scenarios were all variations of baseline scenarios that did not explicitly include aggressive emissions mitigation.

3.2 Future emission scenarios and the carbon cycle

Page 15

FALSE

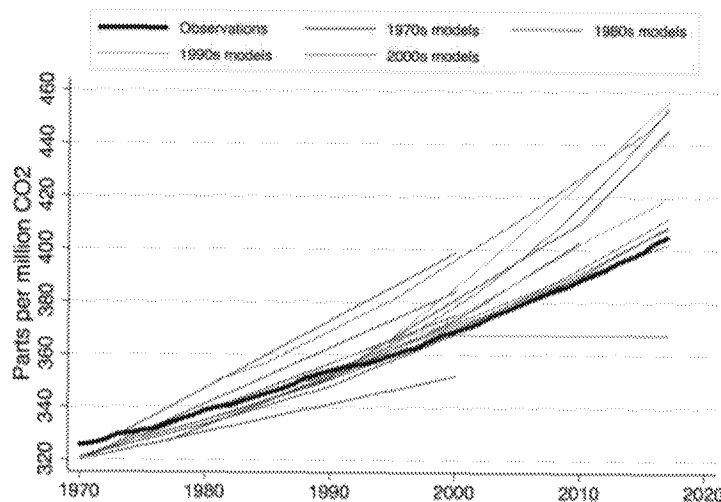


Figure 3.2.1 Since the 1970s successive families of emission and concentration projections (colored lines) have consistently overestimated observations (black line). Source: Hausfather et al. (2019) Figure S4.

[HYPERLINK "<https://berkeleyearth.org/team/>" \l "zeke-hausfather" \h], research scientist, Berkeley Earth

Figure 3.2.1 focuses primarily on older climate models that predate the SRES scenarios. The only SRES scenarios included in the figure are A2 and A1B, and those actually track CO₂ concentrations quite well. The disagreement is primarily with 1970s and 1980s era models; however, as Figure 1 in Hausfather et al. (2019) notes the trend in total forcing in these early models is actually a tad low due to their exclusion of non-CO₂ GHGs.

Quote given to Carbon Brief

Supporting evidence

[HYPERLINK "<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL085378>" \h]

3.2 Future emission scenarios and the carbon cycle

Page 15

MISLEADING

The implausibility of the RCP8.5 scenario was examined by Burgess et al. (2021). The implausibility of RCP8.5 should not be interpreted as very unlikely (e.g. 95th 23 percentile) or a “worst case”, but rather as genuinely implausible owing to the implausibility of the inputs required to reach a forcing

of 8.5 W/m². They noted that RCP8.5 has already diverged from observed trends in energy use and the near future trends diverge sharply from those of the International Energy Agency (IEA), which provides market-based projections of energy use for the coming decades. Pielke Jr. et al. (2022) further showed that the historic and projected IEA trends run near the bottom of the envelopes of both RCP projections and the more recent Shared Socioeconomic Pathway (SSP) scenario trends.

[[HYPERLINK "https://berkeleyearth.org/team/"](https://berkeleyearth.org/team/) \l "zeke-hausfather" \h], research scientist, Berkeley Earth

The authors do not clearly differentiate between the implausibility of a particular emissions scenario like that used to generate RCP8.5 and the forcing outcome of 8.5 watts per meter squared. The latter can come about not just through emissions, but also carbon cycle feedbacks (Hausfather and Betts (2020)). While it remains quite unlikely in my view that we end up at 8.5W/m² by 2100 even with large carbon cycle feedbacks, it is not impossible under a RCP6.0 emissions pathway. Similarly, 8.5W/m² radiative forcing becomes increasingly plausible post-2100 if emissions continue.

3.2 Future emission scenarios and the carbon cycle

Page 16

FALSE

The authors mistakenly conflate total global observed CO₂ emissions in this text with CO₂ emissions from fossil fuels alone (which are shown in Figure 3.2.2). If total CO₂ emissions are used (including land-use emissions), then CO₂ emissions fall right in the middle of the SSPs; in-line with SSP2-4.5 and SSP4- 6.0, below SSP3-7.0 and SSP5-8.5, but above SSP1-1.9, SSP1-2.6 and SSP4-3.4.

3.2 Future emission scenarios and the carbon cycle

Page 17

MISLEADING

There are about 850Gt of carbon (GtC) in the Earth's atmosphere, almost all of it in the form of CO₂. Each year, biological processes (plant growth and decay) and physical processes (ocean absorption and outgassing) exchange about 200GtC of that carbon with the Earth's surface (roughly 80GtC with the land and 120GtC with the oceans). Before human activities became significant, removals from the atmosphere were roughly in balance with additions. But burning fossil fuels (coal, oil, and gas) removes carbon from the ground and adds it to the annual exchange with the atmosphere.

[[HYPERLINK "https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8"](https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8) \h], retired atmospheric physicist

The total mass of carbon in the atmosphere is increasing over time as the carbon dioxide concentration

increases. Crisp et al. (2022) quoted a mass of 877 Peta grams of Carbon (Pg C; one Pg C is equivalent to one billion tonnes of carbon (GtC) or 3.67 billion tonnes of CO₂), which was a good estimate in 2020, when the atmospheric CO₂ dry air mole fraction (a measurement of concentration) was around 412ppm. Here, their estimate of “about 850GtC”, was relevant around a decade ago, when the average CO₂ concentration was closer to 400ppm. The quoted gross annual exchange of carbon between land and the atmosphere and between the ocean and the atmosphere are erroneous and their relative values are reversed. Here, they state that land exchanges 80GtC with the atmosphere and the oceans exchange 120GtC with the atmosphere. They do not cite specific sources for these numbers. They do not come from Crisp et al. (2022). That paper cites gross ocean-atmosphere carbon flux of 90GtC per year and gross land-atmosphere carbon fluxes between 120 and 175GtC per year.

They end this paragraph by noting that the 10.3GtC emitted by fossil fuel use and cement manufacturing is only about 5% of annual emissions by the land biosphere and oceans. This is a half-truth that is clearly intended to be misleading. It fails to recognise that the atmosphere and climate respond to the net emissions and removals of carbon, not the gross fluxes. The land biosphere and ocean both add and remove carbon from the atmosphere, while fossil fuel use and other human activities only add carbon to the atmosphere. When averaged over the globe and over the year, the land biosphere and ocean remove as much carbon as they emit, along with over half of these anthropogenic emissions, yielding net emissions that are negative and only about half as large as the positive anthropogenic emissions. In this context, the net anthropogenic emissions are more than twice as large as the net natural CO₂ fluxes.

3.2 Future emission scenarios and the carbon cycle

Page 18

MISLEADING

The carbon cycle accommodates about 50% of humanity's small annual injection of carbon into the air by naturally sequestering it through plant growth and oceanic uptake, while the remainder accumulates in the atmosphere (Ciais et al. (2013)). For that reason, the annual increase in atmospheric CO₂ concentration averages only about half of that naively expected from human emissions.

[[HYPERLINK "https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8"](https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8) \h], retired atmospheric physicist

Here, the report authors recognise that existing observations show that natural processes in the land biosphere and ocean consistently remove about 50% of the anthropogenic CO₂ emissions. They also note that this ratio has been preserved as the fossil fuel emissions have increased. They attribute the increasing land uptake to the “global greening” phenomena described in chapter 2.1 of this work. However, that chapter fails to recognise that the increasing leaf area index (LAI) does not always indicate increased CO₂ uptake. In particular, as noted in Crisp et al. (2022), many regions of the tropics, where the largest increases in LAI have been seen over the past 50 years, have started to transition from net CO₂ sinks to net sources of CO₂. These changes are due to the impacts of human activities (e.g. deforestation, forest degradation) and climate change (increasing temperature, drought, vapor pressure deficit).

The authors also fail to note that while tropical land is absorbing less CO₂, these losses are being compensated mostly by increased carbon uptake by forests at mid and high latitudes. There, climate change is driving longer, warmer growing seasons and permafrost thaw is allowing trees to grow deeper, more massive

root systems that sequester more carbon in the soil. The rapid growth, combined with higher temperatures and more frequent droughts at these latitudes, result in larger and more frequent wildfires, which release CO₂.

In summary, while the fraction of the anthropogenic CO₂ that has been absorbed by the land biosphere has remained almost constant in response to increasing atmospheric CO₂ abundances, different parts of the world are responding differently to climate change. The focus on "global greening" is a massive oversimplification of the system.

3.2 Future emission scenarios and the carbon cycle

Pages 28-31

MISLEADING

Section 3.2.2: subsections on "CO₂ uptake by land processes" and "CO₂ uptake by ocean processes"

[[HYPERLINK "https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8"](https://www.agu.org/user-profile?cstkey=E0190A3A-0069-416C-8B0C-4048C7E69CB8) \h], retired atmospheric physicist

The last two subsections of this section focus on the carbon cycle models used by the Global Carbon Project. For both land and ocean, they note that this set of models predicts a range of estimates for the decadal uptake of CO₂ by the land and ocean carbon sinks. They use these results to foster doubt in the utility of these methods for predicting future change in the carbon cycle as it responds to climate change. This is interesting because they fail to note that all of the Dynamic Global Vegetation Models (DGVMs) included in this set include CO₂ fertilisation – a mechanism that the authors of this document advocate as a key benefit of increasing atmospheric CO₂ amounts.

3.3 Urbanisation influence on temperature trends

Page 20

MISLEADING

Peterson et al. had failed to find any difference in trends between rural and urban samples, although their definition of rural included local populations up to 10,000 persons while the relative influence of urbanisation begins well below that (Spencer et al. (2025)).

[[HYPERLINK "https://berkeleyearth.org/team/"](https://berkeleyearth.org/team/) \l "zeke-hausfather" \h], research scientist, Berkeley Earth

While Peterson et al. (1999) used a single proxy for urbanity, the follow-up Hausfather et al. (2013) study used four different proxies for urbanity in the conterminous US. It found little residual urban heat island (UHI) bias in the homogenised NOAA data, even when only rural stations are used for breakpoint detection and correction in the homogenisation process to avoid any risk of aliasing in a UHI signal.

3.3 Urbanisation influence on temperature trends

Page 21

MISLEADING

The influence of UHI warming is logarithmic in population, in other words it is strongest at low population density then levels off as local urbanisation expands (Oke (1973) and Spencer et al. (2025)). Hence failure to find a difference in warming rates between urban and rural stations does not prove the absence of UHI contamination.

[[HYPERLINK "https://berkeleyearth.org/team/"](https://berkeleyearth.org/team/) \l "zeke-hausfather" \h], research scientist, Berkeley Earth

This is both overly simplified – the actual environment immediately around the station matters a lot more than regional population density – and not particularly reflective of the literature. Some studies using pretty strict cutoffs for urbanity (e.g. Hausfather et al. (2013)) still find minimal differences in urban and rural stations.

3.3 Urbanisation influence on temperature trends

Page 21

FALSE

In summary, while there is clearly warming in the land record, there is also evidence that it is biased upward by patterns of urbanisation and that these biases have not been completely removed by the data processing algorithms used to produce climate data sets.

[[HYPERLINK "https://berkeleyearth.org/team/"](https://berkeleyearth.org/team/) \l "zeke-hausfather" \h], research scientist, Berkeley Earth

The authors of the DoE report make a strong claim based on papers by some of their team (McKittrick and Spencer) while ignoring other studies that point otherwise. There is by no means agreement that there is a meaningful unremoved UHI bias in land temperatures in the surface record. Indeed, Spencer et al. (2025) only examines raw temperature records and gets a result comparable to that found by Hausfather et al. (2013), but does not do the follow up analysis of homogenised temperature records to see if the UHI bias has been effectively detected and removed (as Hausfather et al. (2013) find that it was).

The analysis in this section also ignores independent assessments by AIRS satellites (global; Susskind et al. (2019)) and the US Climate Reference Network (US; Hausfather et al. (2016)) that show the same rate of warming as the full land station network during the period of overlap, suggesting minimal UHI biases in recent decades. Finally, this section on UHI never bothers to point out that the world is mostly oceans, so even a significant (>10%) bias in land temperatures, if it existed, would have a much smaller effect on resulting global surface temperatures.

Part II: Climate response to CO2 emissions

4.2 Model-based estimates of climate sensitivity

Page 27

FALSE

AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on data-driven methods.

Anonymous

AR6 used multiple lines of evidence in the assessment of climate sensitivity: Understanding of climate processes, the instrumental record, palaeoclimates and model-based emergent constraints. Indeed, the authors of the DoE report contradict their own claim four paragraphs later by saying: "For AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical data and palaeoclimate proxies with the process-based approach." Sherwood et al (2020) used climate models as one of their lines of evidence.

4.3 Data-driven estimates of climate sensitivity

Page 28

MISLEADING

Most climate models simulate that rising GHGs will weaken the west-east temperature gradient, which led the IPCC in AR6 to conclude that data-driven ECS estimates understated the future ECS value. However, Seager et al. (2019) pointed out that, contrary to models, the west-east temperature gradient has been strengthening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterisation of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere"; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate might be lower than current estimates.

[[HYPERLINK "https://ocp.ldeo.columbia.edu/res/div/ocp/people/seager/" \h](https://ocp.ldeo.columbia.edu/res/div/ocp/people/seager/)],
Ewing Lamont research professor, Columbia University

The report is right to point out that we have drawn attention to the fact that the observed gradient has been strengthening while models robustly predict a weakening in response to rising GHGs. The report is also right that we suggested models get the response wrong due to biases in how they simulate the tropical Pacific Ocean...But inferences on the relation between SST, radiation and climate sensitivity for the short time period (strongly influenced by natural internal variability) are not readily transferable to understand these relations for the forced response in the gradient. I don't think we know what

the implications for climate sensitivity are of the problem models have in reproducing the observed pattern of tropical Pacific SST change.

4.3 Data-driven estimates of climate sensitivity

Page 28

MISLEADING

An argument emphasised in AR6 is that data-driven ECS estimates might understate the future warming response to GHGs because of a so-called "pattern effect" (Forster et al. (2021)). The tropical Pacific is believed to strongly influence the overall efficiency with which the Earth radiates heat to space, but some regions remove heat more efficiently than others. If the west- to-east temperature gradient in the tropical Pacific is weakened in a warming climate, warming would concentrate where heat is less efficiently removed, raising ECS.

[[HYPERLINK "https://environment.leeds.ac.uk/see/staff/1267/professor-piers-forster"](https://environment.leeds.ac.uk/see/staff/1267/professor-piers-forster) \h], professor of climate physics, University of Leeds

The citation is ok, but rather offhand and dismissive, given the large amount of evidence assessed on the pattern effect in the IPCC report – it's my chapter 7 which is cited. I also find that the literature on the pattern effect which the section...goes on to discuss is skewed and biased towards suggesting a small GHG cooling. It is especially missing a lot of other literature with conflicting evidence. Lots of literature that we cite in the IPCC report and evidence published since – including my own work – suggests a real pattern effect and high climate sensitivity. If you are going to present conflicting arguments to my IPCC chapter produced by many international authors and three rounds of peer review, including multiple government reviews, I think you would need to explain where these other studies we referenced in IPCC go wrong. I therefore find their argument weak.

4.3 Data-driven estimates of climate sensitivity

Page 28

MISLEADING

A similar argument was recently made by Lee et al. (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere"; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate might be lower than current estimates.

[[HYPERLINK "https://www.ems.psu.edu/directory/sukyoung-lee"](https://www.ems.psu.edu/directory/sukyoung-lee) \h], distinguished professor of meteorology

The report cited my article out of context. Current climate models predict tropical Pacific sea surface

temperature (SST) gradients that do not align with observational trends, whereas the simple model used in my study does. This does not mean that the climate models have no value for predicting the effects

of human activities on future climates. My study simply identified one specific aspect where models may need to be improved to make the predictions more accurate.

Quote given to Carbon Brief

Supporting evidence

[[HYPERLINK "https://link.springer.com/article/10.1007/s00382-023-06741-7"](https://link.springer.com/article/10.1007/s00382-023-06741-7) \h]

5.5 Stratospheric cooling

Page 38

MISLEADING

An important element of the expected general “fingerprint” of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. The latter feature is also influenced by ozone depletion and recovery. AR6 acknowledged that cooling had been observed but only until the year 2000. The stratosphere has shown some warming since, contrary to model projections.

[[HYPERLINK "https://diagrammonkey.wordpress.com/about/"](https://diagrammonkey.wordpress.com/about/) \h], climate scientist

“The poverty of their viewpoint is exemplified in the section on ‘stratospheric cooling’ about one-third of which consists of a long quote from the IPCC AR6 WG1 chapter 2, enough to cite a description of how stratospheric temperatures have changed, but completely ignoring the section on the causes which can be found in section 3.3.1.2.2 of the IPCC WG1 report...They can’t even be bothered to finish the one additional quote that takes up much of the rest of the section, the one from Philipona et al. (2018). The quote, which is from the abstract is cut short with a full stop, where the abstract goes on, after a comma, to say: ‘which is consistent with a reversal from ozone depletion to recovery from the effects of ozone-depleting substances.’ In other words, it’s not that simple and the report relies for its effect on you not digging any further, not even the tiniest little bit.”

5.5 Stratospheric cooling

Page 39

MISLEADING

A combination of tropospheric warming and stratospheric cooling is a commonly cited “fingerprint” of anthropogenic climate change. Stratospheric warming since 2000 coincides with continued surface and tropospheric warming, a pattern that is not found in climate model simulations and is not apparently consistent with the anthropogenic fingerprint.

[[HYPERLINK "https://pcmdi.llnl.gov/staff/santer/"](https://pcmdi.llnl.gov/staff/santer/) \h], atmospheric scientist, Lawrence Livermore National Laboratory

The DoE claim is not true. Climate models can and do show recovery of lower stratospheric temperature after 2000 in response to ozone recovery (and in accord with satellite observations). Over the full satellite era (1986 to 2024), models show very large cooling of the mid- to upper stratosphere in response to human-caused changes in CO2 and ozone (see Fig. 1 in the appended paper).

The observed vertical structure of atmospheric temperature change IS consistent with model predictions and with basic theory. The DoE report cites the appended 2023 Santer et al. PNAS paper as "evidence of absence" of a human fingerprint on the vertical structure of atmospheric temperature. Our 2023 paper actually provides strong evidence FOR the positive identification of this human fingerprint in satellite data.

Quote given to Carbon Brief

Supporting evidence

[[HYPERLINK "https://www.pnas.org/doi/10.1073/pnas.2300758120"](https://www.pnas.org/doi/10.1073/pnas.2300758120) \h]

5.8 US corn belt

Page 42

FALSE

One of the largest discrepancies between models and observations is in the US corn belt, a region of particular importance to global food production. Figure 5.9 shows the warming trends for summertime (June, July, August) for the 12- state corn belt (IN, IA, IL, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973- 2022. All 36 climate models (red) warm far too rapidly compared to observations (blue).

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/) \h], lead author, IPCC AR6 WG2

There is no source for this and no methodological description. I don't believe the comparison between models and observation is correct.

5.8 US corn belt

Page 43

MISLEADING

As discussed in Chapter 9, the anticipated negative effects of increasing temperatures on US corn yields have not materialised, in contrast to widely publicised studies proclaiming that theoretical future impacts are already being experienced (e.g., Seager et al. (2018))

[[HYPERLINK "https://ocp.ldeo.columbia.edu/res/div/ocp/people/seager/"](https://ocp.ldeo.columbia.edu/res/div/ocp/people/seager/) \h],
Ewing Lamont research professor, Columbia University

Our 2018 paper referred to changes in aridity and implications for what crops are grown and farm size and was not about corn yields. We suggest that changes patterns and values of precipitation and potential evapotranspiration would increase aridity over most of the US, which would, in the absence of adaptation, restrict corn cultivation to regions further east. But neither part of the two-part paper claims yields are reducing already due to climate change.

6 Extreme weather

Pages 57-82

MISLEADING

Section 6

[[HYPERLINK "https://emanuel.mit.edu/"](https://emanuel.mit.edu/) \h], professor emeritus of atmospheric science, Massachusetts Institute of Technology

The authors begin sensibly, in the introduction, stating that: 'Climate is about the statistical properties of weather over decades, not single events. Further, there are only about 130 years of reliable observational records that can be analysed statistically. That brief interval does not begin to contain all the extreme events that the climate system can create on its own.' It is odd, then, that they proceed to present timeseries of even shorter length and claim not to find trends of extreme events in them, thereby leading the reader to conclude that there are no underlying trends. They should have just stuck with their original statement and made the correct conclusion that observations usually do not suffice to detect extreme event trends of the predicted magnitude, and then turned to an exposition of what theory and models have to say.

It is very odd that there is almost no mention of theory and models [for] extreme events...Global climate data clearly and unequivocally show this bound increasing in virtually all of the tropical cyclone genesis regions. And, contrary to the statement in the DoE report, an upward trend in the proportion of very strong hurricanes HAS been detected and published. But instead of citing any of this, these authors violate their own introductory statement by citing short and generally unreliable records. For example, they state correctly that there is no detectable trend in continental US hurricane landfalls. But at an average of three landfalling storms per year, there are not nearly enough data to detect a trend of the predicted magnitude. Given that the Caribbean region had a high population density (and associated newspaper accounts) going back to the early 19th century, they could have looked at ALL Atlantic landfalls, not just the US. Had they done so, they would have discovered a clear upward trend.

6 Extreme weather

Pages 57-82

MISLEADING

Section 6

[[HYPERLINK "https://iac.ethz.ch/people-iac/person-detail.html?persid=54778"](https://iac.ethz.ch/people-iac/person-detail.html?persid=54778) \h], head of Institute for Atmospheric and Climate Science, ETH Zurich

The text of chapter 6 often cites chapter 11 of the IPCC AR6, but is a clear example of cherry-picking. The authors repeatedly highlight low-confidence statements from the IPCC AR6 chapter 11 on changes in climate extremes which are mostly on side topics of little relevance, but they rarely cite any high confidence statements from that chapter.

6 Extreme weather

Page 46

MISLEADING

Most types of extreme weather exhibit no statistically significant long-term trends over the available historical record.

[[HYPERLINK "https://iac.ethz.ch/people-iac/person-detail.html?persid=54778"](https://iac.ethz.ch/people-iac/person-detail.html?persid=54778) \h], head of Institute for Atmospheric and Climate Science, ETH Zurich

Importantly, there is no evidence substantiating the claim of the authors of this DOE "critical review" that "most types of extreme weather exhibit no statistically significant long-term trends over the available historical record". It is not clear which types of "extreme weather" the authors refer to, which region(s) they are referring to, and what is the demonstration underlying the claim that "most" of these types exhibit no statistically significant long-term trends. I would ask the authors to provide the arguments substantiating this claim, as there is no rationale provided for this statement in the chapter.

I would also highlight the following conclusions from the IPCC AR6 chapter 11 which provide a very different collective assessment:

- "It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial time, in particular for temperature extremes."
- "Human-induced greenhouse gas forcing is the main driver of the observed changes in hot and cold extremes on the global scale (virtually certain)"
- "The frequency and intensity of heavy precipitation events have likely increased at the global scale over a majority of land regions with good observational coverage. Heavy precipitation has likely increased on the continental scale over three continents: North America, Europe, and Asia."
- "More regions are affected by increases in agricultural and ecological droughts with increasing global warming (high confidence)."
- "It is likely that the global proportion of Category 3–5 tropical cyclone instances has increased over the past four decades."

6.2 Temperature extremes

Pages 63-71

MISLEADING

Section 6.3

[HYPERLINK

"https://usys.ethz.ch/en/people/profile.MTE5NTkw.TG1zdC82MzcsMzIwMTk3MjIy.html" \h], lecturer at the department of environmental systems science, ETH Zurich

The section on hot extremes is an extreme example of cherry-picking results. The report fails to acknowledge that the highlighted regions are some of the very few regions globally where the annual maximum temperatures have not increased (see e.g. IPCC AR6 WG1 Fig. SPM3). The report further highlights that in some regions the number of hottest days have not increased, yet omits that the hottest nights have increased over the same regions and periods (see figure 2.7 in the fifth US National Climate Assessment). Furthermore, the temperature of the warmest nights shows a positive trend over recent decades (Singh et al.2023). The report further fails to refer to the extensive literature discussing the role of land-use changes and irrigation (Mueller et al. (2016)), aerosol forcing (Mascioli et al. (2017)) and unforced internal variability (Singh et al. (2023)) to the regions with little trends.

Supporting evidence

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6.8 Wildfires

Page 70

MISLEADING

Nonetheless just focusing on the post-1985 interval the number of fires [in the US] is not increasing. The area burned did increase but only until about 2007.

[[HYPERLINK "https://www.aparkwilliams.com/"](https://www.aparkwilliams.com/) \h], hydroclimatologist, University of California

The report's section on wildfire lumps the entire US together, smearing out what's going on in the western contiguous US despite the fact that it's the rapidly increasing western US wildfire activity that necessitates this report's wildfire section in the first place. On whether the area burnt in US forest fires has not increased: This is absolutely not the case in the western US, which is again the region that motivates most concerns about wildfire trends in the US. In the western US, the annual area burned has tripled over the past 40 years, driven by a 10-fold increase in annual forest-fire area and a doubling of area burned in non-forest. The western US forest-fire area in 2020 nearly doubled the previous modern record (from 2012) and then 2021 nearly matched 2020. The increase in area burned did not come even close to ending in 2007 in the western US.

On whether fire management practices are responsible for US wildfire trends: Beginning roughly a century ago, the widespread implementation of fire-suppression policies allowed people to effectively take control of wildfire in the western US, but over the past several decades the annual area burned has quickly escalated despite ever intensifying and efforts toward fire suppression. That is, today's concern over wildfire shouldn't depend on how fires of today compare to those of the pre-suppression era, but should instead be related to how the rapidly increasing wildfire sizes in the western US today are occurring despite society's best efforts to avoid such a trend. Further, it's not simply the growing sizes of fires that are of concern. Fire size is simply easy to measure reliably. But as fires have grown larger, they have increasingly put people and property in the paths of flames, had such a negative impact on air quality that trends toward cleaner air since the 1980s have reversed even across much of the eastern US, and rapid increases in the extents of forest area burning at high severities have endangered many forest ecosystems despite fire being a natural ecosystem process."

Quote from [[HYPERLINK "https://science.feedback.org/review/misleading-u-s-department-energy-climate-report-chooses-bias-over-science-climate-scientists-say/"](https://science.feedback.org/review/misleading-u-s-department-energy-climate-report-chooses-bias-over-science-climate-scientists-say/) \h]

7 Changes in sea level

Page 75

FALSE

In evaluating AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the interval has elapsed by 2025, with sea level rising at a lower rate than predicted.

[[HYPERLINK "https://www.pik-potsdam.de/~stefan/"](https://www.pik-potsdam.de/~stefan/) \h], professor of physics of the oceans, University of Potsdam

Possibly they ignored acceleration, an observed fact, thus assuming that in the first half of the period half of

the projected rise should have occurred. But, of course, the IPCC projections account for acceleration, so less than half of the rise should have occurred until now. In fact, projecting sea level rise until 2050 just by extrapolating the observed rise, including the observed acceleration, matches almost exactly the IPCC projections even though these are made in a completely different way.

Looking at the data, for the intermediate point 2030, the AR6 predicts a best estimate 9-10cm, relative to the same base period 1995-2014 (Table 9.9 of AR6 WG1). The satellite data show a rise of 74mm from that base period until 2025. At the same rate, that will be 93mm by 2030, well within in the best-estimate prediction.

Quote given to Carbon Brief

7 Changes in sea level

Page 75

FALSE

US tide gauge measurements reveal no obvious acceleration beyond the historical average rate of sea level rise.

[[HYPERLINK "https://www.pik-potsdam.de/~stefan/" \h](https://www.pik-potsdam.de/~stefan/)], professor of physics of the oceans, University of Potsdam

Most US tide gauges show acceleration, on the east coast that is statistically significant and larger than the global average acceleration, on the west coast less so.

Quote given to Carbon Brief

Supporting evidence

[[HYPERLINK "https://tamino.wordpress.com/2025/08/11/sea-level-rise-in-the-u-s-a/" \h](https://tamino.wordpress.com/2025/08/11/sea-level-rise-in-the-u-s-a/)]

7.1 Global sea level rise

Page 75

MISLEADING

Following the end of the Little Ice Age in the mid-19th century, tide gauges show that the global mean sea level began rising during the period 1820-1860, well before most anthropogenic greenhouse gas emissions.

[[HYPERLINK "https://www.pik-potsdam.de/~stefan/" \h](https://www.pik-potsdam.de/~stefan/)], professor of physics of the oceans, University of Potsdam

While it is true that that's before "most of" greenhouse gas emissions, it is unfair to compare the "start of" the rise with "most of" emissions. The industrial era is usually assumed to start in 1700 and CO2 concentration also starts to rise noticeably around 1820-1860, around the same time as sea level (see the Keeling curve).

Quote given to Carbon Brief

8.3 Attribution of global warming

Page 84

MISLEADING

AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by -0.1C to +0.1C, and internal variability has changed it by -0.2C to +0.2C – on average having essentially no net impact on the warming since 1850-1900.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27560"](https://www.mps.mpg.de/solar-physics/staff/27560) \h],
astrophysicist, Max Planck Institute for Solar System Research

The AR6 report presents this in Fig. SPM.2 as "Aggregated contributions to 2010-2019 warming relative to 1850-1900". This refers to the net effect of various climate drivers on global surface temperature between these two periods, not the maximum changes observed. The accompanying range represents the uncertainty in these estimates. It is therefore misleading to claim that AR6 asserts natural drivers have changed global temperature by $\pm 0.1\text{C}$ since 1850-1900. In reality, Fig. SPM.1 shows that natural variability has led to temperature fluctuations of up to $\pm 0.5\text{C}$ at different times, but the net contribution of natural drivers to long-term warming is estimated at around $\pm 0.1\text{C}$.

8.3 Attribution of global warming

Page 84

MISLEADING

As discussed below, this minimal contribution of natural variability has been disputed by several publications that question the magnitudes of solar variability and internal variability from large-scale ocean circulations.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27561"](https://www.mps.mpg.de/solar-physics/staff/27561) \h],
astrophysicist, Max Planck Institute for Solar System Research

This claim is supported by only a small number of studies that rely on cherry-picked, outdated, or scientifically implausible TSI reconstructions (e.g., Connolly et al. (2021) and (2023); Scafetta (2023); Soon et al. (2023); Grok et al. (2025); and Green and Soon (2025)). All of these studies rely heavily on the Hoyt and Schatten (1993) TSI series, which has been extensively criticised and discredited by Chatzistergos (2024) for its arbitrary adjustments, methodological flaws and use of fabricated data. As such, these claims do not reflect a broadly accepted scientific view. The review by Chatzistergos et al. (2023) provides a comprehensive and up-to-date overview of our current understanding of long-term solar irradiance variations and also explains why the practices underlying such claims are scientifically flawed. I note that although the Chatzistergos et al. (2023) review is cited in the DoE report, it is referenced for an unrelated and irrelevant reason and its core content is disregarded.

8.3 Attribution of global warming

Page 84

AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small (0.05 W/m², Myrhe et al. (2014)).

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27562"](https://www.mps.mpg.de/solar-physics/staff/27562) \h],
astrophysicist, Max Planck Institute for Solar System Research

This is an example of imprecise wording that could be misleading. In AR5, the solar radiative forcing difference between the 1745 and 2008 activity minima was estimated using TSI reconstructions from Wang et al. (2005), Steinhilber et al. (2009) and Krivova et al. (2010). These studies yielded a range of -0.02 to 0.071 Watts per metre squared (W/m²) for the difference (based on seven-year running means, with the caveat that the -0.02 W/m² value comes from Steinhilber et al. (2009), which has a five-year resolution and uses 1965 as the minimum). Based on these estimates, AR5 adopted a range of 0–0.1 W/m² with a central estimate of 0.05 W/m², as explicitly stated in Table 8.SM.4 of the report. However, AR6 defined solar forcing in a different way to reflect the difference between full solar cycles rather than solar minima, as noted in chapter 7 of the WG1 report. This change in methodology is not acknowledged in the DoE report, which may lead to misunderstandings or incorrect comparisons between AR5 and AR6 values.

8.3 Attribution of global warming

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MISLEADING

AR6 acknowledges substantially higher values and a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the 20th century increased by 0.7–2.7 W/m², a range that includes both low and high variability TSI data sets (Gulev (2021)).

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27561"](https://www.mps.mpg.de/solar-physics/staff/27561) \h],
astrophysicist, Max Planck Institute for Solar System Research

The sentence is vague (in particular as to what they refer with "higher values") and potentially conflates two related but distinct concepts: radiative forcing and TSI differences, which were both mentioned but not clearly distinguished. Considering that the previous sentence discusses radiative forcing, one can assume that with "higher values" they refer to radiative forcing too, which would make the statement false. This is easily understood by comparing the statements in AR6 and AR5 about the range of solar radiative forcing.

The AR6 WG1 report (page 958) states:

"In contrast to AR5, the solar effective radiative forcing (ERF) in this assessment uses full solar cycles rather than solar minima. The pre-industrial TSI is defined as the mean from all complete solar cycles from the start of the 14C SATIRE-M proxy record in 6755 BCE to 1744 CE. The mean TSI from solar cycle 24 (2009–2019) is adopted as the assessment period for 2019. The best estimate solar ERF is assessed to be 0.01 W/m², using the 14C reconstruction from SATIRE-M, with a likely range of -0.06 to +0.08 W/m² (medium confidence). The uncertainty range is adopted from the evaluation of Lockwood and Ball (2020), who performed a Monte Carlo analysis of solar activity from the Maunder Minimum to 2019 using several datasets, resulting in an ERF range of -0.12 to +0.15 W/m². The Lockwood and Ball (2020) full uncertainty

range is halved since the period of reduced solar activity in the Maunder

Minimum had ended by 1750 (medium confidence)." By comparison, the AR5 WGI report (page 689) states: "The best estimate from our assessment of the most reliable TSI reconstruction gives a seven-year running mean radiative forcing (RF) between the minima of 1745 and 2008 of 0.05 W/m². Our assessment of the range of RF from TSI changes is 0.0 to 0.10 W/m²."

Thus, the solar radiative forcing estimates in AR5 and AR6 are broadly consistent, with AR6's best estimate slightly lower. If the statement instead refers to TSI differences, this would also be misleading. The AR6 WGI (page 297) lists a TSI difference between the Maunder Minimum and the second half of the 20th century ranging from 0.7 to 2.7 W/m². The lower bound likely corresponds to the SATIRE-T reconstruction, while the upper bound comes from the Yeo et al. (2020) constraint on the dimmest possible state of the sun. It is important to note that Yeo et al. (2020) does not reconstruct TSI during the Maunder Minimum but rather provides a theoretical constraint on the minimum plausible solar irradiance. This constraint effectively excludes TSI reconstructions with large amplitude variability, such as Egorova et al. (2018).

Almost all current TSI reconstructions indicate significantly smaller long-term TSI trends (Chatzistergos et al. (2023)). These include the SATIRE and NRL (now NNL) models recommended for CMIP6 and AR6.

8.3 Attribution of global warming

Page 84

FALSE

The IPCC has only minimally discussed solar influences on global and regional climate.

[[HYPERLINK "http://www.personal.reading.ac.uk/~ym901336/index.html"](http://www.personal.reading.ac.uk/~ym901336/index.html) \h], professor of space environment physics and president of the Royal Astronomical Society, University of Reading

Contrary to this statement, there is much discussion in the last three IPCC assessment reports.

8.3 Attribution of global warming

Page 85

MISLEADING

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990s, before a decline in the early 21st century; this period is often termed the "Modern Maximum" (Chatzistergos et al. (2023); Solanki et al. (2004); Usoskin et al. (2007)). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz (2021)).

[[HYPERLINK "https://www.mps.mpg.de/person/27558/2169"](https://www.mps.mpg.de/person/27558/2169) \h], astrophysicist, Max Planck Institute for Solar System Research

"Although the sentence in which they cite us is factually accurate in isolation, the surrounding text creates a misleading impression. More importantly, our review paper, which they cited, explains why their subsequent paragraph has misleading and wrong statements."

Quote from [[HYPERLINK "https://bsky.app/profile/damagedonegr.bsky.social"](https://bsky.app/profile/damagedonegr.bsky.social) \h]

8.3 Attribution of global warming

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MISLEADING

However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes (2017)).

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27558"](https://www.mps.mpg.de/solar-physics/staff/27558) \h],
astrophysicist, Max Planck Institute for Solar System Research

interpreted as an actual historical TSI difference between the Maunder Minimum and the present, but rather as a physical upper bound on the maximum plausible difference between the sun's dimmest possible state and its current irradiance. Importantly, the Maunder Minimum is unlikely to represent this dimmest state and modern TSI reconstructions suggest a substantially smaller long-term trend than what a 2.7 W/m² Maunder-to-present difference would imply. This upper limit, derived from Yeo et al. (2020), effectively excludes high-variability TSI reconstructions that exceed this threshold. For this reason, the CMIP6 and IPCC AR6 selected two TSI reconstructions, SATIRE (Yeo et al. (2014) and Wu et al. (2018)) and NRLTSI (now referred to as NNLTSI, Coddington et al. (2016), not based on their implied variability magnitude, but because they represent the most advanced, scientifically robust, and rigorously validated models currently available (Matthes et al. (2017)). SATIRE is a semi-empirical, physics-based model, whereas NRLTSI is a proxy-based regression model. Both have undergone extensive scrutiny and show excellent agreement with direct satellite measurements of TSI.

8.3 Attribution of global warming

Page 85

MISLEADING

While AR6 shows a substantially greater solar impact than does AR5, the overall impact of solar forcing on the climate was still assessed to be small compared to anthropogenic forcing.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27558"](https://www.mps.mpg.de/solar-physics/staff/27558) \h], astrophysicist, Max Planck Institute for Solar System Research

The statement is vague and unclear in what it means by “AR6 shows a substantially greater solar impact than AR5”, especially since the same sentence acknowledges that solar forcing was assessed to be small compared to anthropogenic forcing, implying a correspondingly small solar impact. This apparent contradiction likely stems from confusion on the part of the DoE authors regarding the distinction between radiative forcing and total solar irradiance (TSI) differences as presented in AR5 and AR6, as discussed in previous comments.

Quote given to Carbon Brief

8.3 Attribution of global warming

Page 85

MISLEADING

However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood (2012); Connolly et al. (2021)) - something that is not evident in the IPCC assessment reports.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27559"](https://www.mps.mpg.de/solar-physics/staff/27559) \h],
astrophysicist, Max Planck Institute for Solar System Research

AR6 acknowledges the high-variability reconstruction by Egorova et al. (2018) and references studies by Yeo et al. (2020) and Lockwood & Ball (2020), discussing the inherent uncertainty in estimating the secular trend in solar irradiance variations. The earlier study by Lockwood (2012) is not included because its findings are superseded by the more recent Lockwood & Ball (2020). Mike Lockwood was actually one of the contributors to AR6. Thus, IPCCAR6 did adequately discuss the existing uncertainty in irradiance modelling and, thus, its effects on Earth's climate. However, what the authors of the DoE report seem to mean with this sentence is that AR6 does not discuss the Connolly et al. (2021) study. It is worth repeating that the Connolly et al. (2021) paper gave a misleading presentation of the literature. In particular, Connolly et al. (2021) cherry-picked 16 TSI reconstructions, deliberately balancing the sample by including eight with small long-term trends and eight with pronounced trends. However, their inclusion of several outdated or discredited models within the high-variability group is misleading, particularly given the DoE chapter summary's claim that all selected reconstructions are plausible (Chatzistergos et al. (2023) and Chatzistergos (2024)).

As noted in previous comments, the issues with Connolly et al. (2021) undermine the credibility of their results. While there is legitimate uncertainty about the exact magnitude of long-term solar irradiance trends, Connolly et al. (2021) exaggerated the solar impact by cherry-picking outdated and superseded series that display implausibly large TSI variations.

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MISLEADING

There are several rival composite TSI datasets that disagree as to whether TSI increased or decreased during the period 1986-96.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27559"](https://www.mps.mpg.de/solar-physics/staff/27559) \h],
astrophysicist, Max Planck Institute for Solar System Research

It is also important to note that the effect of ACRIM-gap in the trends of the different TSI composites is generally small (Chatzistergos et al. (2023) and Kopp (2025)). While the issue with ACRIM does contribute to the uncertainty in the long-term trend of direct TSI measurements, a growing body of evidence challenges the notion of a TSI increase during the ACRIM-gap, evidence which the DoE report entirely overlooks. Notable examples include Amdur & Huybers (2023), Chatzistergos et al. (2025) and Krivova et al. (2009). By having given such emphasis on the ACRIM-gap the DoE report gives the misleading impression that there can be significant increase in TSI, which could account for the global warming over the same period. Thus, this statement can be misleading.

8.3 Attribution of global warming

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MISLEADING

Further, the satellite record of TSI is used to calibrate proxy models that infer past solar variations from sunspots and cosmogenic isotope measurements (Velasco Herrera et al. (2015)).

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27560"](https://www.mps.mpg.de/solar-physics/staff/27560) \h],
astrophysicist, Max Planck Institute for Solar System Research

There are several issues with this sentence, particularly concerning the choice of the sole reference, which may mislead readers into believing that existing total solar irradiance (TSI) reconstructions depend heavily on direct TSI measurements for determining long-term trends. This is generally incorrect. Moreover, the phrasing gives the impression that only proxy models exist, overlooking the important class of physics-based semi-empirical models

1)Missing relevant literature: The statement omits key papers on irradiance reconstruction models (e.g., Coddington et al. (2016); Wu et al. (2018); and Chatzistergos et al. (2024)) and authoritative reviews (e.g., Chatzistergos et al. (2023) and (2024); and Solanki et al. (2013)) that provide a more accurate and comprehensive perspective.comprehensive perspective.

2)Choice of reference: The DoE cites only Velasco Herrera et al. (2015) to support the claim, which is problematic. That work is not an irradiance reconstruction model but a machine learning extrapolation inherently dependent on the chosen TSI reference series. Given the chaotic nature of solar activity, such extrapolations from limited data lack scientific merit (see Petrovay (2020)). Moreover, the predictions from Velasco Herrera et al. (2015) for 2015–25 are already contradicted by actual direct TSI measurements obtained since.

1) Proxy models: These reconstruct irradiance variations by scaling or regressing solar activity indices against reference TSI data. While the choice of reference series can influence results depending on the regression method, the effect is not always big. For example, Chatzistergos et al. (2020) demonstrated that the choice of TSI reference has negligible impact on minimum-to- minimum trends in their regression model. Similarly, Figure 7c in Chatzistergos et al. (2024) shows only a minor effect of different TSI references on their century-long TSI reconstruction.

2) We have not only proxy models but also physics-based semi-empirical models. Models such as SATIRE and SRPM do rely on tuning some free parameters by comparison to direct TSI measurements. However, this tuning does not significantly affect the long-term trends, as shown in multiple studies (e.g., Chatzistergos et al. (2021)). Notably, Chatzistergos et al. (2025) explicitly states about their irradiance reconstruction with SATIRE-S that "the trend in the updated SATIRE-S TSI composite is independent of measured TSI".

8.3 Attribution of global warming

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MISLEADING

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990s, before a decline in the early 21st century; this period is often termed the "Modern Maximum." (Chatzistergos et al. (2023); Solanki et al. (2004); Usoskin et al. (2007))

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27566"](https://www.mps.mpg.de/solar-physics/staff/27566) \h],
astrophysicist, Max Planck Institute for Solar System Research

The citation of Chatzistergos et al. (2023) in support of the statement about the "Grand Modern Maximum" of solar activity is somewhat misleading. First, the cited paper is a review focused specifically on solar irradiance modeling and long-term trends in irradiance reconstructions. The Grand Modern Maximum is mentioned only briefly in the introduction and is not a subject of analysis in the paper. Moreover, the concept of the Grand Modern Maximum is primarily based on direct sunspot observations, as discussed in works such as Chatzistergos et al. (2017) and Usoskin et al. (2016), which is clearly stated in Chatzistergos et al. (2023), but omitted in the DoE report. The other two studies cited in the DoE, Solanki et al. (2004) and Usoskin et al. (2007), inferred this period in sunspot number series reconstructed from cosmogenic isotope data.

However, these data do not cover the full extent of the modern maximum, and the connection between isotope-based and direct sunspot records remains uncertain. Recent reconstructions like Wu et al. (2018; where both Sami K. Solanki and Ilya G. Usoskin are co-authors) continue to support the existence of a Grand Modern Maximum, but suggest it was less pronounced than earlier assumed.

I presume the authors do not include this study because it was used to reconstruct irradiance variations and returned a rather small secular trend, which would conflict with the claim they want to make here. It is important to recognise that elevated sunspot activity during the second half of the 20th century does not, on its own, determine how much solar irradiance increased, as information on faculae is also essential. Irradiance variations are driven not only by sunspots but also by faculae and network magnetic features. Unfortunately, direct facular observations only extend back to 1892, and their use prior to the 1970s has been rather limited. Consequently, reconstructing past irradiance variations requires assumptions about the relationship between sunspots and faculae, which introduces uncertainty into estimates of the secular trend. However, recent efforts to extract facular information from Ca II K observations (e.g., Chatzistergos et al. (2024)) and to extend irradiance reconstructions back to 1892 indicate only a minimal long-term trend over the 20th century, consistent with state-of-the-art reconstructions such as SATIRE. As mentioned above also updated reconstructions with cosmogenic isotope data (Wu et al. (2018)) suggest a rather small long-term trend. None of this McKittrick (2025) re-examined the Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries (N=862) had complete context is provided in the DoE report, resulting in a potentially oversimplified or overstated implication that a large secular trend is more likely, despite the balance of current evidence.

8.3 Attribution of global warming

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MISLEADING

However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27567"](https://www.mps.mpg.de/solar-physics/staff/27567) \h],
astrophysicist, Max Planck Institute for Solar System Research

This statement is misleading because it refers to section 3 of Schmutz (2021), which focuses on direct measurements of solar irradiance only since 1978, whereas the DoE report in the previous sentence was discussing the grand modern maximum and thus longer-term trends beyond the period covered by direct TSI measurements. Furthermore, the uncertainty in determining the long-term trend, both from direct measurements and modeled reconstructions, is widely acknowledged in the scientific literature and is not limited to a small group of scientists. Nevertheless, all current evidence and advances consistently indicate a relatively weak secular trend in total solar irradiance (TSI) variations.

Quote given to Carbon Brief

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MISLEADING

This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70% of the temperature variability since pre-industrial times (Scafetta (2013); Stefani (2021)).

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27558"](https://www.mps.mpg.de/solar-physics/staff/27558) \h],
astrophysicist, Max Planck Institute for Solar System Research

Neither of the two papers cited for the claim that "datasets with high TSI variability can explain more than 70% of the temperature variability since pre-industrial times". Stefani (2021) did not even use any TSI series; instead, he performed a linear regression between the geomagnetic aa-index and sea surface temperature. Scafetta (2013, p27) states: "Figure 15B compares the Central England Temperature (CET) record and the TSI model by Hoyt and Schatten plus the ACRIM TSI record; an overall good correlation is observed since 1700, which suggests that the major observed climatic oscillations are solar induced and that the sun explains about 50-60% of the warming observed since 1900."

This raises two major concerns. First, the statement in the report is incorrect since neither Scafetta (2013) nor Stefani (2021) demonstrate that TSI can account for "more than 70% of the temperature variability since preindustrial times". Second, the conclusion by Scafetta (2013) relies on the Hoyt and Schatten (1993) TSI model after connecting it to the ACRIM TSI composite. The Hoyt and Schatten 1993 TSI model has been shown to be highly unrealistic and is now widely discredited (Chatzistergos (2024)). As detailed in Chatzistergos (2024), the Hoyt and Schatten model includes multiple arbitrary adjustments and fabricated data for one index spanning over a decade, which appear to have been copied from another index. Critically, the model's high variability was not a result of the model but was imposed by the authors. When updated underlying indices and direct TSI composites (e.g., PMOD, Montillet et al. (2022), ACRIM) are considered, it becomes clear that Hoyt and Schatten (1993) exaggerated TSI variation amplitudes by roughly a factor of five (Chatzistergos (2024)). The discrepancy is even greater when compared to the ACRIM TSI composite, which Hoyt and Schatten's model is incompatible with. This seriously undermines the reliability of conclusions drawn from the Hoyt and Schatten model for attributing recent climate change to solar variability.

Therefore, the two given references do not corroborate the claim of the DoE report. This statement likely originates from Connolly et al. (2023), but the same criticisms previously discussed regarding Connolly et al. (2021) apply here as well. Connolly et al. (2021) and (2023) cherry-picked TSI reconstructions to amplify several outdated or discredited models with high secular trends. As noted in previous comments, these issues undermine the credibility of their results. While there is legitimate uncertainty about the exact magnitude of long-term solar irradiance trends, Connolly et al. (2021) and (2023) exaggerated the solar impact by cherry-picking outdated and superseded series that display implausibly large TSI variations.

8.3 Attribution of global warming

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MISLEADING

The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27559"](https://www.mps.mpg.de/solar-physics/staff/27559) \h],
astrophysicist, Max Planck Institute for Solar System Research

This statement is misleading and confusing. First, the choice of TSI satellite record does not substantially influence the estimated solar contribution to climate change; rather, it is the choice of modelled TSI series, which was the topic of the previous sentence, that can have an impact. Second, as explained above, the high-variability TSI reconstructions used by Connolly et al. (2021) and (2023) to attribute most warming to the Sun are outdated, superseded, and scientifically implausible. While there is indeed uncertainty regarding the long-term trend in solar irradiance, which naturally affects the precise estimate of solar-driven global warming, all current evidence indicates this contribution is relatively small. The sentence in the DoE report, however, dramatically exaggerates this uncertainty and its implications.

However, it is also possible that the authors of the DoE report intended to suggest that the choice of TSI satellite records influences the reconstruction outcomes and thus the estimated solar contribution to global warming. This interpretation would also be misleading, as explained earlier, but reiterated here:

- 1) While the choice of reference TSI series can affect proxy model results depending on the regression approach, this effect is often small. For example, Chatzistergos et al. (2020) demonstrated that the choice of TSI reference has a negligible impact on minimum-to-minimum trends in their regression model. Similarly, Figure 7c in Chatzistergos et al. (2024) shows only minor differences when using various TSI references in their century-long reconstruction.
- 2) This effect is typically negligible in physics-based semi-empirical models. Various studies have confirmed the minimal impact on SATIRE reconstructions when changing the reference TSI series (e.g., Chatzistergos et al. 2021). Notably, for the latest version of SATIRE-S, Chatzistergos et al. (2025) explicitly state that "the trend in the updated SATIRE-S TSI composite is independent of measured TSI".
- 3) As mentioned earlier, the DoE authors cited Velasco Herrera et al. (2015) instead of irradiance reconstruction models, which may have caused the confusion. Velasco Herrera et al. (2015) presented a machine learning extrapolation that inherently depends on the chosen TSI reference series. Given the chaotic nature of solar activity, such limited-data extrapolations lack scientific robustness (see Petrovay (2020)). Moreover, Velasco Herrera et al. 2015 predictions for 2015-25 have already been contradicted by direct TSI measurements collected since.

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FALSE

Scafetta et al. (2023) suggests that ~80% of solar influence on climate might stem from non-TSI mechanisms.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27559"](https://www.mps.mpg.de/solar-physics/staff/27559) \h],
astrophysicist, Max Planck Institute for Solar System Research

The reference is incorrect, there is no Scafetta et al. (2023); this should be Scafetta (2023). Although Scafetta (2023) indeed makes this claim, it is yet another such claim of attributing most global warming to the sun mainly based on the use of the discredited Hoyt and Schatten (1993) TSI series (Chatzistergos (2024)). Scafetta (2023) bases his analysis on a combination of three TSI series: Hoyt and Schatten (1993), Egorova et al. (2018) and the one recommended by CMIP6. Since the Hoyt and Schatten (1993) TSI series was not updated prior to Chatzistergos (2024), Scafetta extended it by linking it to the ACRIM TSI composite. Chatzistergos (2024) demonstrated that the high variability imposed by Hoyt and Schatten (1993) is inconsistent with direct TSI measurements and that a variability magnitude approximately five times smaller is required.

Additionally, Chatzistergos (2024) showed that the Hoyt and Schatten (1993) model conflicts particularly with the ACRIM composite by exhibiting opposite trends during the so-called ACRIM-gap, making Scafetta's extension of Hoyt and Schatten (1993) with ACRIM invalid. Thus, with Egorova et al. (2018) exceeding the Yeo et al. (2020) physical constraint, and considering the multiple methodological issues identified with the Hoyt and Schatten (1993) series (Chatzistergos (2024)), the resulting conclusions by Scafetta (2023) are unlikely. Furthermore, Scafetta himself acknowledged that even when allowing for solar effects beyond radiative forcing, the solar influence remains minimal with the CMIP6 TSI forcing. Therefore, the claim that solar influence accounts for more than 80% of warming is unsupported.

Quote given to Carbon Brief

8.3 Attribution of global warming

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MISLEADING

There are numerous candidate processes, including solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Such solar indirect effects are not included in climate models, although indirect methods of estimating their impacts suggest they are significant.

[[HYPERLINK "https://www.mps.mpg.de/solar-physics/staff/27560"](https://www.mps.mpg.de/solar-physics/staff/27560) \h],
astrophysicist, Max Planck Institute for Solar System Research

It is exaggerated and incorrect to claim that the impacts of such effects are significant. Many of these effects are described vaguely in the DoE report, making their implications unclear (for example, "large relative

changes in the magnetic field") without specifying what that entails. Additionally, the influence of cosmic rays on cloud formation has been shown to be negligible, as demonstrated by the CLOUD experiment at CERN (Pierce (2017)). While some effects on Earth's atmosphere from other processes have been studied (e.g., Mironova et al. (2015) and Sinnhuber & Funke (2020)), their effects are generally considered to be small.

8.3 Attribution of global warming

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MISLEADING

However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, (2017)).

[[HYPERLINK "http://www.personal.reading.ac.uk/~ym901336/index.html"](http://www.personal.reading.ac.uk/~ym901336/index.html) \h
], professor of space environment physics and president of the Royal Astronomical Society, University of Reading

The statement is true, but very misleading as it is made to sound that larger TSI-drift papers were ignored. There is only one very high TSI drift reconstruction and it is very much an outlier – other reconstructions show much smaller drift. There is also analysis of recent solar cycles that shows that the low TSI change reconstructions are correct.

8.3 Attribution of global warming

MISLEADING

However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood (2012); Connolly et al. (2021)) – something that is not evident in the IPCC assessment reports.

[[HYPERLINK "http://www.personal.reading.ac.uk/~ym901336/index.html"](http://www.personal.reading.ac.uk/~ym901336/index.html) \h
], professor of space environment physics and president of the Royal Astronomical Society, University of Reading

This is highly misleading as it conflates regional and global climate. The cited references were discussing regional climates where there is more uncertainty and some (limited) solar influence through downward propagation of stratospheric responses, especially in winter. The global climate is not open to such uncertainty. The cooling (as opposed to warming) of the global stratosphere shows conclusively that the effect of solar change on the global climate is minimal compared to effects of changing solar irradiance.

8.3 Attribution of global warming

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However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability solar variability (Matthes (2017)).

[[HYPERLINK "https://www.geomar.de/en/kmatthes"](https://www.geomar.de/en/kmatthes) \h], director, GEOMAR
Helmholtz Centre for Ocean Research Kiel

It is correct that the long-term trend in TSI is rather on the low variability side, but it is completely ignored that other more extreme trends (high variability trends) are completely unrealistic. We only provide an extreme Maunder Minimum case as a sensitivity experiment.

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MISLEADING

While AR6 shows a substantially greater solar impact than does AR5, the overall impact of solar forcing on the climate was still assessed to be small compared to anthropogenic forcing. However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood (2012); Connolly et al. (2021) – something that is not evident in the IPCC assessment reports. The variations of TSI over time remains a challenging problem. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets that disagree as to whether TSI increased or decreased during the period 1986-96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used to calibrate proxy models that infer past solar variations from sunspots and cosmogenic isotope measurements (Velasco Herrera et al. (2015)). There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990s, before a decline in the early 21st century; this period is often termed the "Modern Maximum". (Chatzistergos et al. (2023); Solanki et al. (2004); Usoskin et al. (2007)). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz (2021)). This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70% of the temperature variability since pre-industrial times (Scafetta (2013); Stefani (2021)). The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

[[HYPERLINK "https://www.geomar.de/en/kmatthes"](https://www.geomar.de/en/kmatthes) \h], director, GEOMAR
Helmholtz Centre for Ocean Research Kiel

In Matthes et al. (2017), we conclude the following two points (just as an example of mis-citation):

1) A new and lower TSI value is recommended: the contemporary solar-cycle average is now 1,361.0 +/- 0.5W/m2 (Prša et al. (2016)).

2) Over the last three solar cycles in the satellite era, there is a slight negative TSI trend in the CMIP6 dataset. A recent reconstruction of the TSI, with a proper estimation of its uncertainties, suggests that this downward trend between the solar minima of 1986 and 2009 is not statistically significant

(Dudok de Wit et al. (2017)). The TSI trend leads to an estimated radiative forcing on a global scale of -0.04 W/m^2 , which is small in comparison with other forcings over this period.

Therefore the sentence in the DoE report stating that the “choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings” is completely wrong and ignores the thorough science. The radiative forcing to this natural forcing – even if we would have chosen a different TSI dataset – is small (-0.04 W/m^2).

The next completely wrong statement is that “such solar indirect effects are not included in climate models”. In Matthes et al. (2017), we provide a comprehensive dataset including TSI and solar spectral irradiance data as well as solar particle forcing for the first time. We also provide an ozone dataset with the indirect effect included. Many of the CMIP6 models do include spectral solar irradiance as well as ozone changes, so the indirect effect and some even the particle effects. I am really shocked about these wrong statements. The IPCC is based on sound scientific evidence and this DoE report is kicking the evidence with feet. Misinterpreting and mis-citing or not at all citing important work (such as the important parts of Matthes et al. (2017) where we provide sound scientific evidence and discuss the details) – this is just horrible. By taking out only parts of the story and “simplifying it”, it is becoming simply wrong. This is not sound science.”

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure 8.2 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m^2 in absorbed solar radiation averaged over the planet (Hansen and Karecha (2025)). For comparison, Forster et al. (2024) estimate the current forcing from the increase in atmospheric CO_2 compared to pre-industrial times to be 2.33 W/m^2 .

[HYPERLINK "<https://environment.leeds.ac.uk/see/staff/1267/professor-piers-forster>" \h], professor of climate physics, University of Leeds

[The citation] is correct, but it presents a somewhat incomplete comparison with the absorbed solar radiation. One's a very long-term forcing, the other is a mix of forcing and response over a shorter period, so the two numbers are not very comparable. All Earth's energy budget terms need to be considered and understood together. And when all components are analysed together, the cause of the Earth's energy balance can be traced to GHG warming and the Earth's system response with a good degree of certainty, as explained by theHodnebrog et al. (2024) paper already referenced. This text as written is ok, but for me it plays up the uncertainties somewhat.

8.4 Declining planetary albedo and recent record warmth

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Arctic sea ice extent has declined by about 5% since 1980

Anonymous

September sea ice (1979-88 average compared to 2015-24 average) is 34% lower today according to OSISAF [Ocean and Sea Ice Satellite Application Facility] observations and 35% lower according to NSIDC [National Snow and Ice Data Center]. For the annual mean sea ice extent, the percentage reduction is 14% according to NSIDC and OSISAF. The number is higher in summer because that is when there is the most sea ice loss and the seasonal minimum, so the least amount to start with. In addition, the evidence given to support this statement links to a figure showing sea ice decline in Antarctica in July.

8.4 Declining planetary albedo and recent record warmth

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MISLEADING

...although following 2007 there has been a pause in the Arctic sea ice decline (England et al. (2025)).

Anonymous

What they say is true and is correctly cited, but lacking context. In the latest version published recently [the DoE report cites a preprint version], the authors note that they “find that the existence of this slowdown also predisposes the sea ice cover for a more rapid decline in the near future”. They add that they “would like to underscore that pause or slowdown are used interchangeably to refer to an extended period with little or no decline in sea ice cover, due to the observed realisation of multi-decadal climate variability on top of the response to anthropogenic forcing, temporarily interrupting the ongoing long-term reduction in Arctic sea ice. This does not imply a cessation of human-induced climate change and, instead, it is likely that sea ice would have increased over this period without human influence.”

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Regarding Antarctic sea ice, the IPCC AR6 concludes that “There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability.” (Summary for Policymakers, A.1.5)

Anonymous

While this is true, it is misleading because they neglect to mention that Antarctic sea ice cover has had a dramatic decline since 2015 and the last few years have seen record lows. Studies have found that these record lows were unlikely to have happened before over the last century. Missing out the last few years of Antarctic sea ice trajectory is a huge omission.

8.4 Declining planetary albedo and recent record warmth

Pages 101-103

MISLEADING

Section 8.4

[HYPERLINK "<https://www.awi.de/en/about-us/service/expert-database/translate-to-english-helge-goessling.html>" \h], climate physicist and group leader, Alfred Wegener Institute

The authors manage to avoid statements that are individually clearly wrong. It is even somewhat difficult to nail down individual sentences that would be clearly misleading taken alone, because that depends on the context they are placed in. However, considering the section as a whole, I think it's pretty clear that they are over-emphasising uncertainties and the possible relative role of natural variability while down-playing the two other main possible mechanisms behind the albedo decline of the last two and a half decades, namely a possibly emerging positive low-cloud feedback and (largely indirect) aerosol effects.

8.4 Declining planetary albedo and recent record warmth

Pages 101-103

MISLEADING

Section 8.4

[HYPERLINK "<https://research.reading.ac.uk/meteorology/people/richard-allan/>" \h], professor of climate science, University of Reading

I did not spot major errors in the section on planetary albedo, although I consider that there is an emphasis on abruptness of temperature and albedo changes, which artificially emphasise the role of natural variability. which could be misleading.

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also increased abruptly in recent years. The question is whether the change is an internal feedback to warming caused by greenhouse gases, or whether something else increased the fraction of absorbed radiation which then caused the recent warming.

[[HYPERLINK "https://research.reading.ac.uk/meteorology/people/richard-allan/"](https://research.reading.ac.uk/meteorology/people/richard-allan/) \h], professor of climate science, University of Reading

A "sharp recent increase in global temperature" and "the fraction of absorbed solar radiation which has also increased abruptly" are potentially misleading since while both global surface temperature and absorbed solar radiation have varied with ENSO, they have also increased steadily over time (Loeb et al. (2024) and Forster et al. (2024)). This wording could artificially emphasise the role of natural variability.

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth.

[[HYPERLINK "https://research.reading.ac.uk/meteorology/people/richard-allan/"](https://research.reading.ac.uk/meteorology/people/richard-allan/) \h], professor of climate science, University of Reading

Planetary albedo has decreased before 2015 as well as after, though the decreases are larger around 2012-14 (increases in absorbed sunlight in Loeb et al. (2024), Fig. 5a). Decreases in reflected sunlight up to 2016 are captured by some climate models applying observed SST (Loeb et al. (2020)), suggesting that they are a response to global warming and its spatial pattern (Andrews et al. (2022)), though it is not clear how much of the pattern of global warming is explained by radiative forcing and how much internal variability.

8.4 Declining planetary albedo and recent record warmth

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MISLEADING

The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade: • Natural climate variability • Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha (2025))

[[HYPERLINK "https://www.awi.de/en/about-us/service/expert-database/translate-to-english-helge-goessling.html"](https://www.awi.de/en/about-us/service/expert-database/translate-to-english-helge-goessling.html) \h], climate physicist and group leader, Alfred Wegener Institute

Maybe even more importantly, they omit the third major possible mechanism behind the cloud-cover decline altogether, namely indirect aerosol effects. They do mention aerosols and recent aerosol emission reductions, but only prior to the part where they state that the main reason for the albedo-decline seems to be related to clouds (which, by itself, is true). They write: "The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade." However, the indirect aerosol effect, although uncertain, is likely even stronger than the direct aerosol effect, and it is an important candidate for explaining a part of the recent cloud-cover decline. By omitting this completely,

they further emphasise the relative importance of natural variability to a degree that can not be considered appropriate.

Quote given to Carbon Brief

8.4 Declining planetary albedo and recent record warmth

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MISLEADING

Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

[[HYPERLINK "https://research.reading.ac.uk/meteorology/people/richard-allan/"](https://research.reading.ac.uk/meteorology/people/richard-allan/) \h], professor of climate science, University of Reading

Surface albedo has also contributed significantly to the decline in global albedo according to Loeb et al. (2024), which accounts for cloud masking: "...part of the positive –SW trend is impacted by decreases in surface albedo from declining sea-ice coverage during the CERES period". However, this applies to the period since 2000, rather than during 2015, which line 10 [of the DoE report] is referring to, while the decrease in planetary albedo has been observed over the full CERES period rather than just in 2015 (Loeb et al. (2024)).

8.4 Declining planetary albedo and recent record warmth

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MISLEADING

Loeb et al. found that decreases in low- and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the northern hemisphere, whereas in the southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones.

[[HYPERLINK "https://research.reading.ac.uk/meteorology/people/richard-allan/"](https://research.reading.ac.uk/meteorology/people/richard-allan/) \h], professor of climate science, University of Readinga

The stated "decreases in low- and mid-level clouds" is misleading since Loeb et al. (2024) find decreases in cloud cover and also reflectance have contributed to the increase in absorbed sunlight along with surface albedo decreases (that can be related to ice melt elsewhere in the article): "[W]e find that decreases and middle cloud fraction and reflection and reduced reflection from cloud-free areas in mid-high latitudes are the primary reasons for increasing ASR [absorbed solar radiation] trends in the [northern hemisphere]...In the [southern hemisphere] the increase in ASR is primarily from decreases in middle cloud reflection and a weaker reduction in low-cloud reflection." The increase in reflection counters arguments presented that the decreases in aerosol are not influencing the decreases in albedo as their effect on making clouds brighter diminishes (e.g.

Hodnebrog et al. (2024)), while the additional steady rise in ASR during the CERES period is also consistent with cloud and ice-albedo feedbacks to warming (Forster et al. (2021); Tselioudis et al. (2025); and Norris et al. (2016)) as well as declining global aerosol emissions (Quaas et al. (2022)).

8.4 Declining planetary albedo and recent record warmth

Page 91

MISLEADING

The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade: • Natural climate variability • Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha (2025))

[[HYPERLINK "https://research.reading.ac.uk/meteorology/people/richard-allan/"](https://research.reading.ac.uk/meteorology/people/richard-allan/) \h], professor of climate science, University of Reading

Two explanations for decreased global albedo are presented, but the decline in ocean aerosols is ignored and this has been identified as an important driver of decreased global albedo (e.g. Hodnebroeg et al. (2024)). Combined with overemphasis of the abruptness of changes, this is potentially misleading since it overemphasises the role of natural variability.

8.4 Declining planetary albedo and recent record warmth

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MISLEADING

It is not easy to justify a new positive low cloud feedback that began emerging in 2015 since there is no obvious feedback trigger starting at that time.

[[HYPERLINK "https://www.awi.de/en/about-us/service/expert-database/translate-to-english-helge-goessling.html"](https://www.awi.de/en/about-us/service/expert-database/translate-to-english-helge-goessling.html) \h], climate physicist and group leader, Alfred Wegener Institute

I think this is an example of a "straw man argument", because it's clear that there would not be a trigger starting exactly at some point. Rather, a forced signal (like a positive cloud feedback) would be superimposed by natural variations, and at some point, depending on signal-to-noise ratio (and possible other forcings) and how the associated forcing grows, the forced signal can emerge from the noise. An associated timeseries may just look like something kicked in at a specific time.

8.4 Declining planetary albedo and recent record warmth

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However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds: • The 2014-16 was one of the strongest El Niño events on record. • A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al. (2017); Arthun et al. (2021)). • The Pacific Decadal Oscillation positive index peaked in 2016, then declined and has been in negative territory since late 2019. • Eruption of the submarine Hunga-Tonga volcano in 2022.

[[HYPERLINK "https://www.awi.de/en/about-us/service/expert-database/translate-to-english-helge-goessling.html"](https://www.awi.de/en/about-us/service/expert-database/translate-to-english-helge-goessling.html) \h], climate physicist and group leader, Alfred Wegener Institute

When it comes to natural variability, they are listing quite comprehensively which aspects of natural variations could – in principle – have had an impact on planetary albedo, in part also overemphasising some aspects that rather clearly can not have had a major impact on the longer-term decline, such as ENSO (as we also investigated in our paper). Also their interpretation of results for the Hunga Tonga eruption and its possible contribution to the recent warming surge seems not to be a balanced representation of the recent literature about it, which does not suggest a major contribution. Also, they provide their list of natural variability aspects right after the down-playing statement about the possible low-cloud feedback mentioned above, saying: “However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds.” This shows quite clearly that they want to emphasise the natural variability over the possible low-cloud feedback.

Quote given to Carbon Brief

8.4 Declining planetary albedo and recent record warmth

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MISLEADING

It is not easy to justify a new positive low cloud feedback that began emerging in 2015 since there is no obvious feedback trigger starting at that time.

[[HYPERLINK "https://research.reading.ac.uk/meteorology/people/richard-allan/"](https://research.reading.ac.uk/meteorology/people/richard-allan/) \h], professor of climate science, University of Reading

A change in the SST pattern has been linked to a decline in low-altitude cloud over some stratocumulus regions (Andrews et al. (2022) and Loeb et al. (2020)) and it is misleading to paint these changes as requiring new feedbacks.

Quote given to Carbon Brief

8.4 Declining planetary albedo and recent record warmth

MISLEADING

A change of 1-2% in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO₂.

[[HYPERLINK "https://research.reading.ac.uk/meteorology/people/richard-allan/"](https://research.reading.ac.uk/meteorology/people/richard-allan/) \h], professor of climate science, University of Reading

Short-term interannual fluctuations are unfairly compared with long-term radiative forcing. Also, a decrease in global albedo is an expected consequence of global warming as feedbacks cause ice to melt and some clouds to diminish (e.g. Forster et al. (2021)). This signal in shortwave radiation is seen to a greater extent than in the longwave since decreases in outgoing longwave due to rising greenhouse gases being offset by the increases in outgoing longwave from the resulting higher temperatures that are influenced by the greenhouse gases, but also declining aerosol and feedbacks that amplify the warming through ice melt and cloud responses to warming (e.g. Raghuraman et al. (2024)).

8.6 Extreme event attribution (EEA)

Page 96

FALSE

The existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al. (2020)). Methods to eliminate the bias have not yet been established.

[[HYPERLINK "https://iac.ethz.ch/people-iac/person-detail.html?persid=335613%20https%3A//people.epfl.ch/anthony.davison%3Flang%3Den"](https://iac.ethz.ch/people-iac/person-detail.html?persid=335613%20https%3A//people.epfl.ch/anthony.davison%3Flang%3Den) \h], research scientist, professor of mathematics, ETH Zurich, École Polytechnique Fédérale de Lausanne

The text suggests that the presence of the trigger event at the end can't be dealt with, whereas the argument in Barlow and in our paper is that it can be dealt with (if the selection event is known) with appropriate statistical methods specifically detailed in both papers.

8.6 Extreme event attribution (EEA)

Page 96

MISLEADING

Methods to eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison (2023)) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain that it should be avoided altogether.

[[HYPERLINK "https://iac.ethz.ch/people-iac/person-detail.html?persid=335613%20https%3A//people.epfl.ch/anthony.davison%3Fla ng%3Den"](https://iac.ethz.ch/people-iac/person-detail.html?persid=335613%20https%3A//people.epfl.ch/anthony.davison%3Fla ng%3Den) \h], research scientist, professor of mathematics, ETH Zurich, École Polytechnique Fédérale de Lausanne

The cited paper does argue that the estimated return period is highly variable and so one should avoid using it, but also states that if it has to be used, one should clearly state its uncertainty. It does not imply that fast weather attribution should not be performed at all.

8.6 Extreme event attribution (EEA)

Page 97

MISLEADING

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: "The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate."

[[HYPERLINK "https://usys.ethz.ch/en/people/profile.MTE5NTkw.TGlzdC82MzcsMzIwMTk3MjIy.html"](https://usys.ethz.ch/en/people/profile.MTE5NTkw.TGlzdC82MzcsMzIwMTk3MjIy.html) \h], lecturer at the department of environmental systems science, ETH Zurich

The quote taken from the paper Zeder et al. (2023) led by my (former) PhD student, Joel Zeder, is in itself correct, yet taken completely out of context. Our paper shows indeed that when using relatively short observational timeseries, return level estimates may be systematically underestimated and return periods may be overestimated, which affects the calculation of the risk ratio in attribution studies. We further concluded that the risk of extreme heatwaves could be underestimated in both past and present-day climate and recommend following an approach like Miralles and Davison (2023). This paper applied the recommended approach specifically to the 2021 Pacific north-west heatwave.

However, both Miralles and Davison (2023) and Zeder et al. (2023) show that while methodological choices affect the exact estimate of the risk ratio, all estimates show a strong role of long-term warming increasing the probability of the event.

Part III: Impacts on ecosystems and society

9.1 Econometric analyses

Page 104

FALSE

Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modelling.

[[HYPERLINK "https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/"](https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/) \h], researcher in economics, INRAE & University Paris-Saclay

Bareille and Chakir (2023) do reproduce the standard results obtained from “conventional econometric modelling” like the Ricardian approach proposed by Mendelsohn et al. (1994). However, these standard results in no way demonstrate “negative effects of warming on agricultural land values”. Rather, as illustrated in Figure 5 of their study, Bareille and Chakir (2023) closely mimic the outcomes of the Ricardian approach in similar contexts, which points to slightly positive impacts of climate change on farmland values. Such findings are consistent with the broader literature when applied to contexts with moderate climate conditions. Nevertheless, as has been extensively discussed, these results are likely subject to bias arising from omitted variables.

9.1 Econometric analyses

Page 104

FALSE

But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture.

[[HYPERLINK "https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/"](https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/) \h], researcher in economics, INRAE & University Paris-Saclay

Bareille and Chakir (2023) do not identify any negative impacts of climate change on land values; across all methodologies they employ, the evidence consistently points toward positive effects of recent climate trends.

Quote given to Carbon Brief

9.1 Econometric analyses

Page 104

MISLEADING

But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture.

[[HYPERLINK "https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/"](https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/) \h], researcher in economics, INRAE & University Paris-Saclay

These results are derived from recent climate trends over the period 1990-2020 in the context of French agriculture. While such moderate warming may generate short-term benefits for agriculture, more substantial – and as yet unobserved – warming is likely to result in losses. It is well established that higher temperatures induced by climate change can produce non-linear effects, with moderate warming potentially yielding gains, but more pronounced warming leading to detrimental impacts.

Quote given to Carbon Brief

9.1 Econometric analyses

Page 104

MISLEADING

But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture.

[[HYPERLINK "https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/"](https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/) \h], researcher in economics, INRAE & University Paris-Saclay

While such a result may arise in contexts like France (where northern regions remain, for the time being, too cold to cultivate high-value crops), these findings are highly context-specific and cannot be generalised to other settings. This is particularly true for a large and heterogeneous country like the US, where both climatic and agricultural conditions differ substantially from those in France. Bareille and Chakir (2023) provide indirect evidence that the positive impacts of recent climate change on French agriculture identified with their approach are likely driven by vineyard expansion, a phenomenon highly specific to France and not transferable to the US context.

9.1 Econometric analyses

Page 104

MISLEADING

The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

[[HYPERLINK "https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/"](https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/) \h], researcher in economics, INRAE & University Paris-Saclay

These results are obtained using a novel method, the so-called repeat-Ricardian approach. In contrast to other studies cited in the report – such as Mendelsohn et al. (1994), Deschênes and Greenstone (2007), Schlenker and Roberts (2009) and Burke and Emerick (2016) – this approach has not yet been replicated in other contexts. Its findings should therefore be interpreted with caution. By comparison, dozens of replications and extensions of Deschênes and Greenstone (2007), Schlenker and Roberts (2009) and Burke and Emerick (2016) consistently document negative impacts of climate change on crop productivity in the US, but also worldwide.

9.1 Econometric analyses

Page 105

MISLEADING

A major deficiency of all these studies, however, is that they omit the role of CO2 fertilisation. Climate change as it relates to this report is caused by GHG emissions, chiefly CO2. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO2 that drives them.

[[HYPERLINK "https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/"](https://psae-saclay.fr/en/membres-de-lunite/francois-bareilleinrae-fr/) \h], researcher in economics, INRAE & University Paris-Saclay

All of these studies implicitly account for the effects of CO2 fertilisation on agriculture insofar as local CO2 concentrations are correlated with changes in temperature and precipitation. Moreover, Hultgren et al. (2025) show that the positive effects of CO2 fertilisation only partially offset the negative impacts of anthropogenic climate change on crop yields arising from changes in temperature and precipitation.

9.2 Field and laboratory studies of CO2 enrichment

Page 105

MISLEADING

One of the ways the effect of CO2 on crop growth has been studied is through “free air enrichment experiments” or FACE plots, in which small sources of CO2 are placed in fields surrounding plants and the growth response to elevated CO2 under varying weather conditions are recorded. Ainsworth et al. (2020) summarises results from about 250 such studies. They found that elevation of CO2 by 200ppm caused an average 18% increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

[[HYPERLINK "https://lab.igb.illinois.edu/long/"](https://lab.igb.illinois.edu/long/) \h], Ikenberry Endowed University Chair, University of Illinois

While this report is correct in saying that, in isolation, our research has shown that an increase in CO2 does (on average for C3 crops) results in increased yields and decreased quality, and that it can increase water

use efficiency. But when account is taken of the accompanying changes in tropospheric ozone, temperature, atmospheric water vapor pressure deficit and extreme drought, heat and flooding events then the overall effect of GHG driven climate and atmospheric change is strongly negative.

Quote given to Carbon Brief

9.3 Crop modeling meta-analyses

Page 107

MISLEADING

McKittrick (2025) re-examined the Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries (N=862) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the records most commonly missing were the changes in ambient CO₂ and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables, thereby increasing the usable sample size by 40%. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 9.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5C warming (green lines).

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/) \h], lead author, IPCC AR6 WG2

Regression analysis of historical climate impacts on crop yield do not capture the impact of non-linear processes, such as effects of extreme heat stress occurring at crop anthesis. Hence the conclusion based on a single approach is misleading (Moore et al. (2017) and McKittrick (2025)). The IPCC assessed a range of peer-reviewed publications based on regression analysis and process-based models, also including the CO₂ fertilisation effects (for example, see AR6 WG2, chapter 14, p1,956, for synthesis on US agriculture).

9.4 CO₂ fertilization and nutrient loss

Page 107

MISLEADING

Evidence has shown that CO₂-induced biomass gains are sometimes accompanied by reductions in the concentrations of protein and other key nutrients such as iron and zinc (Ebi et al. 2021)."

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

All plants absorb carbon dioxide from the atmosphere, using photosynthetic pathways to break down that carbon dioxide into carbon and oxygen, and then using the carbon to grow. Eighty-five percent of plants use a photosynthetic pathway that, based on biochemical characteristics, is termed C3; these C3 plants include important crops such as wheat, rice, barley, oats, rye, soybean and potatoes. Field experiments with wheat and rice under a doubling of CO₂ from pre-industrial concentrations demonstrate that protein declines by about 10%, B-vitamins by as much as 30% and micronutrients by about 5% (see Ebi et al. (2021) and associated references). Wheat and rice each provide about 20% of calories consumed worldwide, with wide regional variability (Awika (2011) and Shiferaw et al. (2013)). Corn, sorghum and millet use a different photosynthetic pathway (C4) and are not expected to experience declines in nutrient density with higher CO₂ concentrations. The DoE CWG report conflates these two photosynthetic pathways into “sometimes” without being clear that declines in nutrient density are consistently seen under elevated CO₂ for C3 crops (Loladze (2002) and (2014); Loladze et al. (2019); Myers et al. (2014); Taub et al. (2008); J. Wang et al. (2019) and (2020); and Zhu et al. (2018)), which are widely consumed in the US.

The DoE CWG report also ignores a key fact raised in Ebi et al. (2021) that elevated CO₂ and elevated temperature can increase toxins such as arsenic and cadmium in crops (Dhar et al. (2020); Farhat et al. (2021) and (2023); Guo et al. (2011); Muehe et al. (2019); J. Wang et al. (2019); Y. Wang et al. (2023); and Yuan et al. (2021)), not just dilute nutrients. Ingestion of toxins in food results in illness, shortened life span, reduced quality of life and death (Gibb et al. (2019)).

9.4 CO₂ fertilization and nutrient loss

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MISLEADING

Some experiments have shown that the rising temperatures expected to accompany higher CO₂ levels will offset this loss (Köhler et al. (2019)) although the evidence for this is mixed, as is the evidence that nutrient dilution observed to date is entirely attributable to higher CO₂ (Ziska (2022)).

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

Some experiments have shown that rising temperatures expected to accompany higher CO₂ levels can offset nutritional losses (Köhler et al. (2019) and, while the DoE CWG report acknowledges that evidence for this temperature compensation is mixed, it fails to cite studies that found partial or no compensation in nutritional density when elevated CO₂ was crossed with elevated temperature (e.g., Jayawardena et al. (2021); J. Wang et al. (2019); Wei et al. (2021); and Ziska et al. (1997)). On the flip side of crop nutritional quality, increased temperatures are expected to increase toxin levels in crops. Wang et al. (2020) found that while warmer temperatures moderately mitigated the loss of nutrients associated with elevated CO₂, the warmer temperatures simultaneously increased manganese, molybdenum, chromium, nickel, cadmium and lead concentrations in rice and wheat. A study investigating arsenic contamination of rice found that grain arsenic concentrations were more elevated when elevated CO₂ was combined with elevated temperature than when either elevated CO₂ or elevated temperature operated alone (Muehe et al. (2019)).

The second half of the statement above (i.e., “... as is the evidence that nutrient dilution observed to date is entirely attributable to higher CO₂”) draws an incorrect conclusion from Ziska (2022). Ziska (2022) presents a figure (Figure 1) that shows newer breeding lines of spring wheat have less percent protein, but that all the breeding lines have experienced declines in percent protein over the 20th century. Thus, Ziska (2022)

acknowledges that breeding can change nutritional density but ultimately concludes that “[CO₂] is directly affecting protein concentration separate from breeding history”.

Quote given to Carbon Brief

9.4 CO₂ fertilization and nutrient loss

Page 107

MISLEADING

If nutrient dilution does occur under rising CO₂ levels, there are several adaptive strategies that could be pursued. First, selective breeding to raise micronutrient content is already established (Saltzman et al. (2017)) and has proven to be a cost-effective agronomic strategy (Ebi et al. (2021)).

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

Biofortification via selective breeding has been used successfully to raise the zinc, iron and vitamin A content of crops, per Saltzman et al. (2017). However, this approach is not a “proven” agronomic strategy, cost-effective or otherwise, for addressing simultaneous nutrient dilution by elevated CO₂. Ebi et al. (2021) specifically stated: “An additional challenge for biofortification is the tendency of rising CO₂ concentrations to diminish the concentrations of multiple nutrients concomitantly (Loladze (2014a) and (2014b)) in contrast to biofortification that targets only one or a few selected nutrients.” Further, biofortification cannot address the issue of increased toxin levels in crops associated with elevated CO₂ and CO₂-induced warming.

References

Page 108

FALSE

*Deryng, D., Elliott, J., Folberth, C. et al. (2021) Regional disparities in the beneficial effects of rising CO₂ concentrations on crop water productivity. Nature Climate Change 6, 786–790 (2016).
<https://doi.org/10.1038/nclimate2995>*

[[HYPERLINK "https://www.iri-thesys.org/people-pages/delphine-deryng-dr/"](https://www.iri-thesys.org/people-pages/delphine-deryng-dr/) \h], lead author, IPCC AR6 WG2

The date of the citation is incorrect, and I didn't find reference to this paper in the text of the chapter
Quote given to Carbon Brief

9.4 CO₂ fertilization and nutrient loss

MISLEADING

Optimal strategies will be location-specific because they vary by crop, climate and soil type (Ebi et al. (2021)).

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

Developing new cultivars requires significant investments and generally take years (see CGIAR programmes). Such programmes will not be developed locally, nor will the investment make sense if the developed cultivar only applies to a specific location.

9.4 CO2 fertilization and nutrient loss

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MISLEADING

Second, fortification of food products with micronutrients is already routine. Folic acid (a B vitamin) is added to flour and many other foods; iodine is added to table salt, most commercial breakfast cereals are fortified with iron and numerous vitamins, etc. Third, dietary supplements in the form of multivitamin tablets are inexpensive, widely-available and routinely consumed.

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

Fortification and dietary supplements do not currently alleviate nutrient deficiencies; therefore, it is unlikely that such approaches will alleviate nutrient deficiencies in the future, particularly if they are exacerbated by lower crop nutrient density. For example, 30% of women and girls worldwide (15-49 years) currently have iron-deficiency anemia (World Health Organization, 2025), including nearly 40% of women and girls (12-21 years) in the US (Weyand et al. (2023)). These deficiencies exist despite decades of dietary supplement availability (Macdougall (2017)). The DoE CWG report ignores that high CO2 concentrations affect a wide range of macro and micronutrients beyond iron and zinc, such as lithium (for mental health), magnesium (for muscle and nerve function, blood pressure regulation, bone health and energy production) and others (Loladze (2014)). Dietary supplements do not address these critical contributions to hidden hunger (Wallace et al. (2014)). US government guidelines emphasise that supplements are not an adequate substitute for a nutrient dense diet (US Department of Agriculture and US Department of Health and Human Services (2010)). Further, fortification of food or use of supplements will not address the health risk posed by increased toxin concentrations in grain associated with elevated CO2 and CO2-induced warming.

9.4 CO2 fertilization and nutrient loss

Page 108

MISLEADING

One concern about reliance on adaptive strategies is whether they are feasible in low-income countries. Micronutrient deficiency is already a problem in the developing world and dietary supplements have proven to be an effective low- cost response (Ebi et al. (2021)).

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

As noted in the previous comment, micronutrient deficiency is a health problem in developing and developed countries; dietary supplements have not solved the problem. Micronutrient deficiency is expected to increase with elevated CO₂ (Beach et al. (2019); Smith and Myers (2019); Weyant et al. (2018); and Zhu et al. (2018)). As supplements have been unable to fully address the current deficiencies in micronutrients, it is unlikely they will successfully ameliorate a future increased health burden caused by nutrient dilution in crops. In addition, as noted in the previous comment, supplements will not address the health issues posed by increased toxin concentrations in grain expected with elevated CO₂ and CO₂-induced warming.

9.4 CO₂ fertilization and nutrient loss

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MISLEADING

It should also be noted the IPCC emission scenarios that generate high levels of warming also involve strong income growth. The SSP scenarios assume that, compared to 2005 levels, global per capita income will double by 2100 in the lowest growth case (SSP3), and in the highest emission case (SSP5) global per- capita income will grow nearly 16-fold. In that scenario even the poorest regions (Africa and the Middle East) end up with a per capita income of about US\$126,000, 70% higher than current US per capita income (about US\$75,000). Consequently the same scenarios in which CO₂ levels increase the most are also those in which global poverty is largely eliminated, in which case all countries would be able to afford dietary supplements as necessary to address micronutrient deficiencies, if they arise and cannot be addressed using on- farm agricultural strategies.

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

The US is one of the wealthier countries in the world, yet many US citizens suffer from micronutrient deficiencies. Wallace et al. (2014) used data from the National Health and Nutrition Examination Survey (2007-10) to determine that despite the fact that 51% of Americans consume multivitamin/mineral supplements with greater than nine micronutrients, many fail to meet the estimated average requirement for vitamin A (35%), vitamin C (31%), vitamin D (74%), vitamin E (67%), vitamin K (77%), calcium (39%), magnesium (46%), potassium (100%) and choline (92%). Bird et al. (2017) concluded that “nearly one-third of the US population is at risk of deficiency in at least one vitamin, or has anemia”.

Growth and development of children and lifespan health depends on adequate intake of micronutrients. Decreasing the nutrient density of diets through continued emissions of CO₂ will exacerbate the situation, even with any associated income growth. Ingestion of toxins in food is a global problem that affects the health of millions of people, including those living in wealthy countries (Consumer Reports (2012) and (2014); and Gibb et al. (2019)). A growth in income will not offset the health risk posed by contaminated food. It is

expected that this health risk will grow as elevated CO₂ and CO₂-induced warming increase the toxin content of crops (Dhar et al. (2020); Farhat et al. (2021) and (2023); Guo et al. (2011); Muehe et al. (2019); J. Wang et al. (2019); Y. Wang et al. (2023); and Yuan et al. (2021)).

9.4 CO₂ fertilization and nutrient loss

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MISLEADING

In summary, there is abundant evidence going back decades that rising CO₂ levels benefit plants, including agricultural crops, and that CO₂-induced warming will be a net benefit to US agriculture. To the extent nutrient dilution occurs there are mitigating strategies available that will need to be researched and adapted to local conditions.

[[HYPERLINK "https://interactive.carbonbrief.org/doe-factcheck/index.html"](https://interactive.carbonbrief.org/doe-factcheck/index.html) \h], and Dr Becca Neumann, associate professor of civil and environmental engineering

There is abundant evidence that under ideal conditions (i.e., adequate nutrients and water and optimal temperatures), crop productivity increases with rising CO₂ levels (e.g., Ainsworth & Long (2020)). These increases diminish or disappear when conditions are non-ideal (i.e., nutrients are limited, water and temperatures are sub-optimal). As CO₂ concentrations increase, ambient temperatures will continue warming and weather patterns will shift, altering water and nutrient availability. It is not clear that boosts in productivity generated by elevated CO₂ will compensate for the damage to plant productivity caused by these other stressors. In many parts of the world, even with adaptation, crop yields are expected to decline (Hultgren et al. (2025)).

Further, discussed in the comments above, elevated CO₂ is associated with declining nutrient density in crops. Therefore, it is disingenuous to state that there is “abundant evidence going back decades that rising CO₂ levels benefit plants”. This statement cherry-picks the productivity boost to plants associated with rising CO₂ levels while ignoring the negative human health outcomes that will co-occur. The scientific consensus is that CO₂-induced warming will be harmful to US agriculture, leading to yield declines (Hu et al. (2024); Hultgren et al. (2025); Lobell et al. (2011); Lobell and Field (2007); and Zhao et al. (2017)). Physiological studies of crops show there is an optimal temperature at which yields maximise. When temperatures are below or above this optimal point, yields decline.

Further, as outlined in the comments to Section 9.4 above, CO₂-induced warming is associated with increased toxin levels in crops. It is factually inaccurate to state that “CO₂-induced warming will be a net benefit to US agriculture”. There are strategies, such as biofortification and supplementation, that can be employed to help mitigate nutrient dilution in crops, as discussed in Ebi et al. (2020). However, as outlined in the comments above, these approaches currently do not address nutrient deficiencies and therefore it is unrealistic to expect that they will be able to address future nutrient deficiencies exacerbated by rising CO₂ levels and crop nutrient density. Further, these strategies will not solve the problem of increased concentrations of toxins in crops associated with increased CO₂ and/or CO₂-induced warming.

10.3 Mortality from temperature extremes

Pages 122-124

MISLEADING

Section 10.3.1

[[HYPERLINK "https://www.lshtm.ac.uk/aboutus/people/gasparrini.antonio"](https://www.lshtm.ac.uk/aboutus/people/gasparrini.antonio) \h], biostatistician and epidemiologist, London School of Hygiene & Tropical Medicine

In relation to my area of research, the report cites two articles (Gasparrini (2015) and Zhao (2021)) in support of the statement that cold-related mortality far exceeds heat-related mortality in most of the regions. While true, this says little about the impact of climate change on temperature-related deaths. In fact, the focus should be on the respective (and opposite) change in the heat and cold contributions, not their absolute values. In this respect, there is some evidence that the expected reduction in cold-related mortality will not offset the increase in heat-related mortality, in particular under more extreme climate change scenarios (Gasparrini (2017) and Masselot (2025)). More importantly, the level of adaptation to heat required to offset such a positive net effect should be very high, in the order of 90% reduction (Masselot (2025)).

Quote given to Carbon Brief

11 Climate change, the economy, and the social cost of carbon

Page 116

FALSE

An influential study in 2012 suggested that global warming would harm growth in poor countries, but the finding has subsequently been found not to be robust. Studies that take full account of modelling uncertainties either find no evidence of a negative effect on global growth from CO2 emissions or find poor countries as likely to benefit as rich countries.

[[HYPERLINK "https://profiles.sussex.ac.uk/p289812-richard-tol"](https://profiles.sussex.ac.uk/p289812-richard-tol) \h], professor at the department of economics, University of Sussex

“The second sentence is wrong. The authors refer to “studies”, but without references. Tol (2024) finds that the then-available studies jointly point to a negative impact of climate change on global economic growth. My less systematic reading of the literature since has not led me to change my mind. Their conclusion that ‘poor countries’ are ‘likely to benefit’ is again not backed up with references. Tol (2024), the only reference in the paragraph, concludes the opposite.”

11.1 Climate change and economic growth

MISLEADING

Nor have past extreme weather events had a significant effect on US banks’ performance (Blickle et al. (2021)); warming has even been shown to be beneficial for the finance and insurance sector (Mohaddes et al. (2023)).

[[HYPERLINK "https://www.jbs.cam.ac.uk/people/kamiar-mohaddes/" \h](https://www.jbs.cam.ac.uk/people/kamiar-mohaddes/)],
deputy director of the Cambridge executive MBA programme,
University of Cambridge

“The way our findings have been presented is misleading...Investigating the long-term macroeconomic effects of climate change across 48 US states, we provide evidence for the damage that climate change causes in the US using various economic indicators at the state level: growth rates of Gross State Product (GSP), GSP per capita (income), labour productivity and employment as well as output growth in 10 economic sectors (e.g. agriculture, manufacturing, services, retail and wholesale trade). Just to be clear, (1) these are not ‘small negative effects’ and (2) we do indeed show that climate change has negative effects on income in the US. We show that while hashtag#weather shocks have level effects (or temporary growth impacts), climate change – by shifting the long-term average and variability of weather – impacts the US economy’s ability to grow in the long term! We study economic activity in all sectors of the US economy –agriculture, forestry & fisheries; mining, construction, manufacturing, transport, communications and public utilities, wholesale trade, retail trade, financial services & property, services and government –and find that the impact of climate change on sectoral output growth is broad based – each of the 10 sectors considered is affected by at least one of the four climate variables.”

11.2 Models of the social cost of carbon

Page 121

MISLEADING

Economists use IAMs to compute the SCC. Two of the best-known are the Climate Framework for Uncertainty, Negotiation and Distribution (“FUND”, Tol 1997) and Nordhaus’ DICE. EPA (2023) introduced new ones for its recent work. IAMs embed a “damage function” or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

[[HYPERLINK "https://profiles.sussex.ac.uk/p289812-richard-tol/" \h](https://profiles.sussex.ac.uk/p289812-richard-tol/)], professor at the department of economics, University of Sussex

“The literature is vast. I counted 446 papers with estimates. There are numerous commentaries; and two handfults of meta-analyses (e.g. Tol (2023) and Moore et al. (2024)). Instead, the authors wrote their own review, which omits the most influential papers and misses key insights. Cherry-picking may be a better term than review.”

11.2 Models of the social cost of carbon

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FALSE

Tol (2017) estimates that the private benefit of carbon is large relative to the social cost.

[[HYPERLINK "https://profiles.sussex.ac.uk/p289812-richard-tol" \h](https://profiles.sussex.ac.uk/p289812-richard-tol)], professor at the department of economics, University of Sussex

“This paper was never published in a peer-reviewed journal and is therefore not admissible by the rules of the US government. The paper was peer-reviewed and rejected, because my private benefit [of carbon] is an average, whereas the social cost is a marginal. The two cannot be compared (unless you make a ridiculous assumption about linearity). I still hope to fix the paper one day. As it stands, however, the comparison is wrong.”

Quote from [[HYPERLINK "https://richardtol.substack.com/p/is-climate-change-dangerous" \h](https://richardtol.substack.com/p/is-climate-change-dangerous)]

ny No. 07222041

Fig 8.4.5

Number of days $\geq 95^{\circ}\text{F}$

Line	Dashed	Dash	Dash	solid	solid	solid	solid
	PacSW	PacNW	4Crns	NPIns	SPIns	UMidW	OhVly
1899-04	226.87	52.44	177.12	48.23	240.6	17.61	71.75
1905-10	246.06	58.9	156.64	43.43	252.04	12.52	36.88
1911-16	199.73	46.82	144.22	46.2	315.36	29.34	109.8
1917-22	249.24	60.09	161.85	63.02	287.09	19.65	73.52
1923-28	243.99	62.09	160.34	41.87	304.58	13.4	61.64
1929-34	262.64	69.52	185.1	106.45	352.83	53.69	133.09
1935-40	261.61	69.43	199.82	115.18	337.97	42.35	106.54
1941-46	226.36	52.44	167.46	52.52	279.87	14.63	74.02
1947-52	234.63	40.2	182.8	57.34	307.28	19.59	54.35
1953-58	230.37	45.29	193.15	60.83	365.82	21.53	90.8
1959-64	245.47	56.6	184.33	67.11	273.38	10.24	34.97
1965-70	248.82	60.42	157.92	54.57	234.28	8.87	29.52
1971-76	243.4	56.28	161.78	60.7	192.9	14.34	26.07
1977-82	238.95	51.77	182.54	50.11	293.96	11.52	43.48
1983-88	238.61	52.9	166.58	73.72	250.86	28.1	63.76
1989-94	233.65	52.69	176.58	41.43	200.48	5.86	25.61
1995-00	236.45	52.28	186.83	46.05	285.7	6.73	32.24
2001-06	282.35	71.74	214.31	73.19	244.03	9.83	30.58
2007-12	271.04	54.61	203.74	53.55	290.75	9.86	53.07
2013-18	292.46	72.52	200.35	41.8	246.15	3.9	15.35
2019-24	317.1	85.76	242.01	62.73	296.85	7.41	25.31

solid	solid	columns
SoEst	NoEst	US48
125.58	9.14	121.36
91.13	4.85	113.43
129.88	13.78	132.27
110.96	11	130.91
138.61	8.6	131.52
163.7	17.5	169.74
126.03	10.49	162.16
127.49	12.25	127.91
124.37	12.05	133.31
144.8	14.18	151.93
83.47	5.63	123.58
68.56	5.02	109.31
41.83	3.54	99.8
116.47	4.34	128
104.28	11	124.6
75.27	6.63	102.48
107.37	7.28	124
63.89	8.93	125.66
125.07	9.57	136.11
68.19	5.14	118.27
92.85	8.16	143.76

10 Managing Risks of Extreme Weather

10.1 Socioeconomic context

Risks from human-caused climate change are convoluted with natural weather and climate variability, and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as US population grew from 76 million in 1900 to over 331 million in 2020 (Goklany, 2011). For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01% of the US population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006% of the US population) (NOAA, 2025; USCB, 2025).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify (Deryugina and Hsiang 2023). US weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation (NRC 2010). Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B (NBER, 2024).

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992) have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes (FEMA, 2020). Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012) (BMI, 2013). Inland dams in the US help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers (TVA, 2025). During Hurricane Helene (2024), TVA's strategies prevented approximately \$406M in potential damages (APPA, 2024).

10.2 Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the Billion Dollar Disaster series as evidence that climate change is making extreme weather worse (R Pielke Jr., 2024). But over time, population and wealth have increased dramatically in the US, so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. Pielke Jr. (2024) demonstrates that losses per weather disaster are down by about 80% since 1980, as a proportion of GDP. Pielke Jr. (2024) also argued that in addition to relying on opaque data sources and unreported adjustments NOAA failed to normalize its Billion Dollar Disaster data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from

publication (R Pielke Jr., 2025).

10.3 Mortality from temperature extremes

10.3.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. It stands to reason that extreme heat events would likely become more frequent while extreme cold events would become less frequent. This pattern is evident in the historical period though not in the continental US (Chapter 6) and is expected to continue with further warming.

Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes is typically caused by hypothermia and heart strain. Global mortality is substantially greater for cold conditions than for hot conditions (Zhao et al 2021, Ritchie 20214). Unlike with heat-related mortality, cold-weather risks set in even at moderately cold conditions (Gasparini et al. 2015, Lee and Dessler 2023). A 13-country study of 74 million deaths from 1985 to 2012 estimated that, on average, 7.7% of deaths were attributable to sub-optimal temperatures, of which 7.4% were attributable to cold and only 0.4% were attributable to heat (Gasparini et al. 2015). In other words cold weather killed 18.5 times as many people as did hot weather.

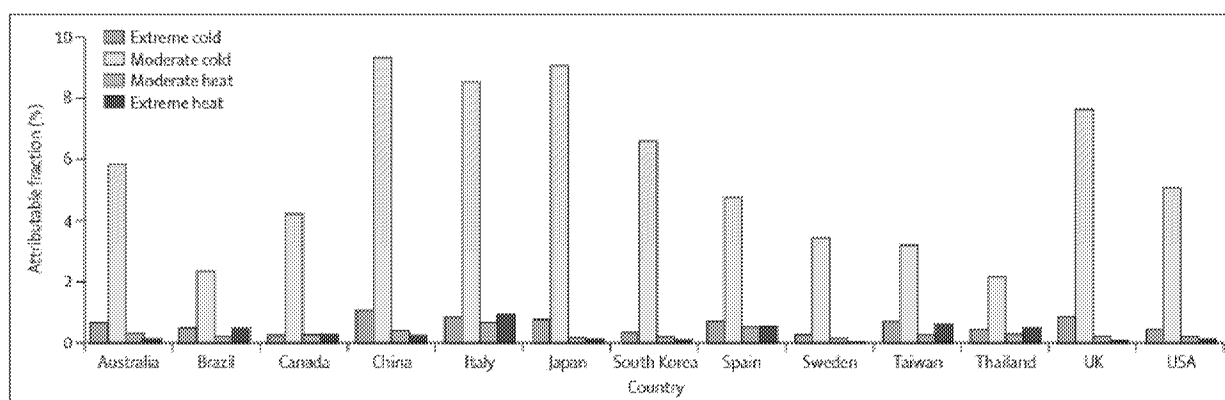


Figure 10.3.1. Mortality attributable to extreme and moderate cold and heat by country. Source: reproduced from Gasparini et al. (2015).

Figure 10.3.1 shows the distribution of results from Gasparini et al. (2015) by country. For the United States the fraction of deaths attributable to temperature was 5.9%, of which 5.5% was due to cold, thus cold weather killed 14 times as many people as hot weather.

There is strong evidence that people adapt to weather risks. Lee and Dessler (2023) reported that 86% of temperature-related deaths across 40 cities in the U.S. were due to cold-related mortality, and that due to adaptation the relative risk of death declined in hot and cold cities alike as seasonal temperatures increased. Allen and Sheridan (2018) found that short, early-season cold events were 2 to 5 times deadlier than hot events, but the mortality risk of both cold and hot extremes drops to nearly zero if the events occur late in the season.

Davis et al. (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb et al. (2014) examined mortality data for 106 million people in over 100 cities U.S. cities

and found a 60% decline in average heat-related mortality over the period 1987—2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million deaths in 211 U.S. cities from 1962 to 2006, Nordio et al. (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, by reducing mortality from cold events rising temperatures are associated with a net saving of lives.

The IPCC AR6 Working Group 2 Chapter 16.2.3.5 (O'Neill et al. 2022) acknowledges that heat-related mortality risk is declining over time:

“Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.”

It is both disappointing and telling to see how the IPCC misrepresents the situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

10.3.2 The importance of adaptation

The observed decline in US heat-related mortality has been specifically attributed to adaptation. Wang et al. (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live Wang et al. project not only no increase in heat-related mortality but an overall decrease for the US as a whole. They conclude that

“Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves... Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.”

10.3.3 Mortality risks and energy costs

A 2016 study of US long term mortality risks associated with temperature variations (Barreca et al. 2016) showed that increases in mortality across the US are associated both with cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through

conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus et al. (2022) showed that wealthy and poor households in the US adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels ($< 5^{\circ}\text{C}$) energy spending in high-income households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days ($> 30^{\circ}\text{C}$) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

10.4 Summary

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. U.S. mortality risks even under extreme warming scenarios are not projected to increase as long as people are able to undertake adaptive responses.

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Impacts of Carbon Dioxide Emissions on the U.S. Climate

CONFIDENTIAL DRAFT FOR DISCUSSION PURPOSES

Ad hoc Climate Working Group
United States Department of Energy
May 28, 2025

CONFIDENTIAL DRAFT FOR DISCUSSION PURPOSES

Impacts of Carbon Dioxide Emissions on the U.S. Climate

Report to US Energy Secretary Christopher Wright

May 28, 2025

Ad hoc Climate Working Group:

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKittrick, Ph.D.

Roy Spencer, Ph.D.

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SECRETARY'S FOREWORD

Energy, Integrity, and the Power of Human Potential

Over my lifetime, I've had the privilege of working as an energy entrepreneur across a range of fields—nuclear, geothermal, natural gas, and more—and I now serve as Secretary of Energy under President Donald Trump. But above all, I'm a physical scientist who sees modern energy as nothing short of miraculous. It powers every aspect of modern life, drives every industry, and has made America an energy powerhouse with the ability to fuel global progress.

The rise of human flourishing over the past two centuries is a story worth celebrating. Yet we are told—relentlessly—that the very energy systems that enabled this progress now pose an existential threat. Hydrocarbon-based fuels, the argument goes, must be rapidly abandoned or else we risk planetary ruin.

That view demands scrutiny. That's why I commissioned this report: to encourage a more thoughtful and science-based conversation about climate change and energy. With my technical background, I've reviewed reports from the Intergovernmental Panel on Climate Change, the U.S. government's assessments, and the academic literature. I've also engaged with many climate scientists, including the authors of this report.

What I've found is that media coverage often distorts the science. Many people—even well-meaning ones—walk away with a view of climate change that is exaggerated or incomplete. To provide clarity, I asked a diverse team of independent experts to summarize the current state of climate science, with a focus on how it relates to the United States.

I didn't select these authors because we always agree—far from it. In fact, they may not always agree with each other. But I chose them for their rigor, honesty, and willingness to elevate the debate. I exerted no control over their conclusions. What you'll read are their words, drawn from the best available data and scientific assessments.

I've reviewed the report carefully and challenged its findings. I believe it faithfully represents the state of climate science today. Still, many readers may be surprised by its conclusions—which differ in important ways from the mainstream narrative. That's a sign of how far the public conversation has drifted from the science itself.

To correct course, we need open, respectful, and informed debate. That's why I'm inviting public comment on this report. Honest scrutiny and scientific transparency should be at the heart of our policymaking.

Climate change is real, and it deserves attention. But it is not the greatest threat facing humanity. That distinction belongs to global energy poverty. As someone who values data, I know that improving the human condition depends on expanding access to reliable, affordable energy. Climate change is a challenge—not a catastrophe. But misguided policies based on fear rather than facts could truly endanger human well-being.

We stand at the threshold of a new era of energy leadership. If we empower innovation rather than restrain it, America can lead the world in providing cleaner, more abundant energy—lifting billions out of poverty, strengthening our economy, and improving our environment along the way.

EXECUTIVE SUMMARY

This report reviews scientific certainties and uncertainties in how anthropogenic carbon dioxide (CO₂) emissions have affected, or will affect, the Nation's climate, extreme weather events, and selected metrics of societal well-being. Those emissions are increasing the concentration of CO₂ in the atmosphere through a complex and variable carbon cycle, where some portion of the additional CO₂ persists in the atmosphere for centuries.

Elevated concentrations of CO₂ enhance plant growth, globally "greening" the planet and increasing agricultural productivity. They also decrease ocean alkalinity by an amount within the range of natural variability. That is possibly detrimental to coral reefs, although the recent rebound of the Great Barrier Reef suggests otherwise.

Carbon dioxide also acts as a greenhouse gas, exerting a warming influence on climate and weather. The world's several dozen detailed climate models offer little guidance on how the climate responds to that influence, with the average surface warming under a doubling of the CO₂ concentration ranging from 1.8°C to 5.7°C, generally higher than simpler, data driven estimates, which suggest 1.8°C

Detailed climate models generally run "hot" in their description of the climate of the past few decades - too much warming at the surface, in the lower- and mid-troposphere, and too much amplification of warming aloft. They also produce too much recent stratospheric cooling, too much water vapor increase, too much snow loss, and too much warming in the corn belt. The combination of overly sensitive models and extreme scenarios for future emissions has exaggerated projections of future warming.

Most extreme weather events do not show long-term trends. Claims of increased frequency or intensity of hurricanes, tornadoes, floods, and droughts are not supported by historical data. Additionally, forest management practices are an often-overlooked factor in assessing wildfire activity. Global sea level has risen approximately 8 inches since 1900, but there are significant regional variations in tide gauge data driven primarily by local land subsidence; U.S. tide gauge measurements in aggregate do not show any long-term sea level acceleration.

The attribution of particular climate changes or extreme weather events to human CO₂ emissions is challenged by natural climate variability, data limitations, and inherent model deficiencies. Moreover, solar activity's contribution to the warming climate may be underestimated.

Both models and experience suggest that CO₂-induced warming may be less significant economically than commonly believed, and excessively aggressive mitigation policies could prove more detrimental than beneficial. Social Cost of Carbon estimates, which attempt to quantify the economic damage of CO₂ emissions, are highly sensitive to their underlying assumptions and so provide limited independent information.

The report supports a more nuanced and evidence-based approach to climate policy. The risks and benefits of a climate changing under both natural and human influences must be weighed against the costs, efficacy, and collateral impacts of any "climate action", taking into account the nation's need for reliable and affordable energy with minimal local pollution. Assumptions about future emissions should be grounded in reality. Climate models should be re-evaluated to address biases and uncertainties, and the limitations of event attribution studies should be clearly acknowledged. An approach that acknowledges both the potential risks and benefits of CO₂, rather than relying on flawed models and extreme scenarios, is essential for informed and effective decision-making.

INTRODUCTION: OVERVIEW AND PURPOSE OF THIS DOCUMENT

This document originated in late March 2025 when Secretary Wright assembled an independent group to write a report on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions endanger the US public. We agreed to undertake the work on the condition that there would be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The group began working in early April with a deadline of May 28. The short timeline and the technical nature of the material meant that we could not comprehensively review all topics. While the report is intended to be accessible for non-experts, we have omitted some introductory or explanatory material that can easily be accessed elsewhere. Nor have we attempted to survey entire literatures related to the topics covered. We have focused as much as possible on literature published since 2020 and referenced previous IPCC and NCA assessment reports. We have also used data through 2024 where possible.

The writing team is grateful to Secretary Wright for the opportunity to prepare this report and for his support of independent scientific assessment.

May 2025

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKittrick, Ph.D.

Roy Spencer, Ph.D.

PART I: DIRECT HUMAN INFLUENCE ON ECOSYSTEMS AND THE CLIMATE

1 CARBON DIOXIDE AS A POLLUTANT

Chapter summary

Carbon dioxide (CO₂) differs in many ways from the so-called Criteria Air Pollutants. It does not affect local air quality and has no human toxicological implications at ambient levels. It is an issue of concern because of its potential effects on the global climate, a complex issue that occupies much of this report.

The Clean Air Act of 1970 defined six so-called Criteria Air Contaminants subject to regulation (EPA): particulate matter, ground-level Ozone, Sulfur Dioxide, Nitrogen Dioxide, Lead and Carbon Monoxide (CO). In 2007, the Supreme Court ruled that greenhouse gases (CO₂ among them) were also “pollutants” subject to regulation under Clean Air Act (*Mass. v. EPA*, 2007). While the definition of “pollutant” is ultimately a legal one, there are important scientific distinctions between CO₂ and the Criteria Air Contaminants. The latter are subject to regulatory control because they cause local problems depending on concentrations that include nuisances (odor, visibility), damage to plants, and, at high enough exposure levels, toxicological effects in humans. In contrast, CO₂ is odorless, does not affect visibility and has no toxicological effects at ambient levels. It is a naturally occurring part of the atmosphere and a key component of human and plant respiration. CO₂ is essential for plant photosynthesis and higher levels are beneficial for vegetation. In these aspects, CO₂ is similar to water vapor.

Ambient outdoor air today contains about 430 parts per million (ppm) CO₂, increasing at about 2 ppm per year. The US Occupational Safety and Health Administration issues guidelines for indoor workplaces in which elevated CO₂ might be encountered, such as where dry ice is used. The Permissible Exposure Limit is 5,000 ppm over 8 hours (OSHA, 2024). Allen et al. (2015) reported evidence of diminished performance on some cognitive tasks among workers in office cubicles when exposed to CO₂ levels above 1,000-1,500 ppm. These levels are far larger than any plausible ambient outdoor value through the end of the 22nd century.

The growing amount of CO₂ in the atmosphere directly influences the earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and by neutralizing ocean alkalinity. But the primary concern about CO₂ is its role as a greenhouse gas (GHG) that alters the earth’s energy balance. How the climate will respond to that influence is a complex question that will occupy much of this report.

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2 DIRECT IMPACTS OF CO₂ ON THE ENVIRONMENT

Chapter summary

CO₂ enhances photosynthesis and improves plant water use efficiency, thereby promoting plant growth. Global greening due to increased CO₂ levels in the atmosphere is well-established on all continents.

CO₂ absorption in sea water reduces the alkalinity of the oceans. The recent decline in alkalinity is within the range of natural variability on millennial time scales. Most ocean life evolved when the oceans were mildly acidic. Declining alkalinity might adversely affect corals, although the Australian Great Barrier Reef has shown considerable growth in recent years.

2.1 CO₂ and global greening

The growing CO₂ concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency. That is evident in the “global greening” phenomenon discussed below, as well as in the improving agricultural yields discussed in Chapter 10.

2.1.1 Measurement of global greening

“Greening” refers to an increase in the fraction of the Earth’s surface covered by plants. It can be quantified by the “Leaf Area Index” (LAI) measured by satellite. Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO₂ levels. Zhu *et al.* (2016) was one of the first studies to report that global greening was detectable using satellite sensors. From 1982 to 2011 they detected greening over 25-50% of the Earth versus “browning” over only 4% and attributed 70% of the greening to rising CO₂ levels (see Figure 2.1).

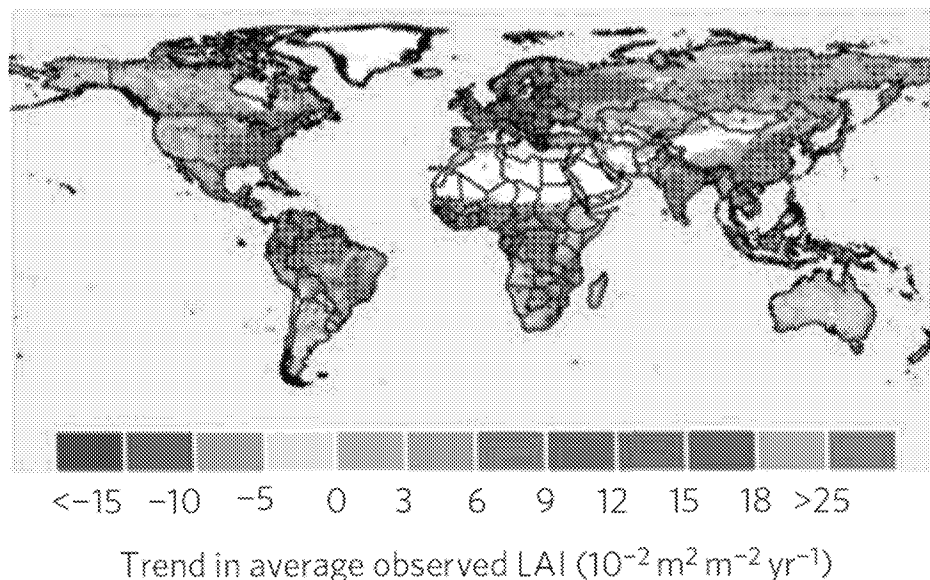


Figure 2.1: Trends in average Leaf Area Index (LAI). Source: Zhu et al. 2016 Figure 3.

Zheng (2017) confirmed the pattern, noting that greening over thirty years had added 8% to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen et al. (2019) noted that China and India were exploiting it through land management changes. Thus, while China accounts for only 6.6% of global vegetated area it accounts for 25% of global net increase in LAI. Piao et al. (2020) noted that greening was even observable in the Arctic.

While plant models predict increased in photosynthesis in response to rising CO₂, Haverd et al. (2020) reported a CO₂ fertilization rate nearly double what models had predicted. That is, CO₂ fertilization had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. This indicates that global models of the socioeconomic impacts of rising CO₂ have likely understated the benefits to crops and agriculture. The connection between CO₂ fertilization and climate policy will be discussed in Chapter 10.

Finally, Chen et al. surveyed claims that greening had slowed since 2000 due to drought stress. They found instead that faulty satellite sensors were the cause and that the corrected data showed accelerated greening over 55% of the globe while browning was accelerating over only 7%. In other words, the greening trend continued with no evidence of slowdown, and CO₂ fertilization remained the dominant driver

2.1.2 Photosynthesis and CO₂ levels

Plants build biomass through *photosynthesis*, a process that converts carbon dioxide, water, and light into sugar. The plant enzyme responsible for photosynthesis is called Ribulose-1,5-bisphosphate-carboxylase/oxygenase or “Rubisco”. Photosynthesis is initiated when CO₂ is available at the surface of the RuBisCo enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass. This is referred to as the “C3” process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth’s atmospheric CO₂ levels were usually many times higher than they are today, as shown in Figure 2.2.

About 400 million years ago CO₂ levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd et al. 2024). Over the past 35 million years the level of atmospheric CO₂ has been steadily declining. During glaciations levels have fallen as low as 170 ppm (Gerhart and Ward 2010).

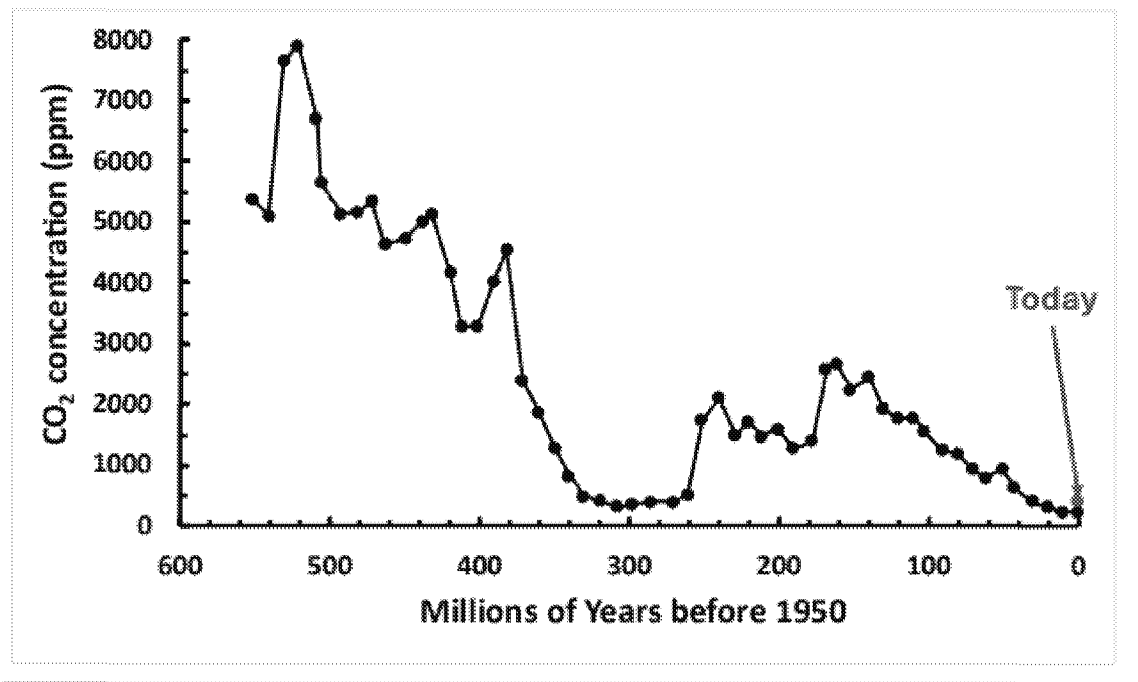


Figure 2.2. Ambient CO₂ levels over the past 550 million years. Today's concentration of 430 ppm is also shown. Source: (Berner 2006)

In response to low-CO₂ conditions some plants evolved another photosynthetic pathway called C₄, in which CO₂ is concentrated in the vicinity of Rubisco allowing for the C₃ process to function more efficiently. For agricultural purposes the plant categories are:

- C₃: rice, wheat, soybeans and most other crops
- C₄: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO₂ levels continued declining, plant growth rates would have declined and eventually ceased. Below 180 ppm many C₃ species experience growth rate reductions on the order of 40-60% compared to their growth rates at 350 ppm (Gerhart and Ward 2010). C₃ plants have been observed under experimental conditions to stop growing altogether at levels between 60—140 ppm CO₂. Some C₄ plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Currently, CO₂ levels are about 420 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO₂ is illustrated in Figure 2.3 which is reproduced from Gerhart and Ward (2010). It shows the growth effect of CO₂ on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO₂ exposure is varied. The gains exhibited from increasing CO₂ from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.

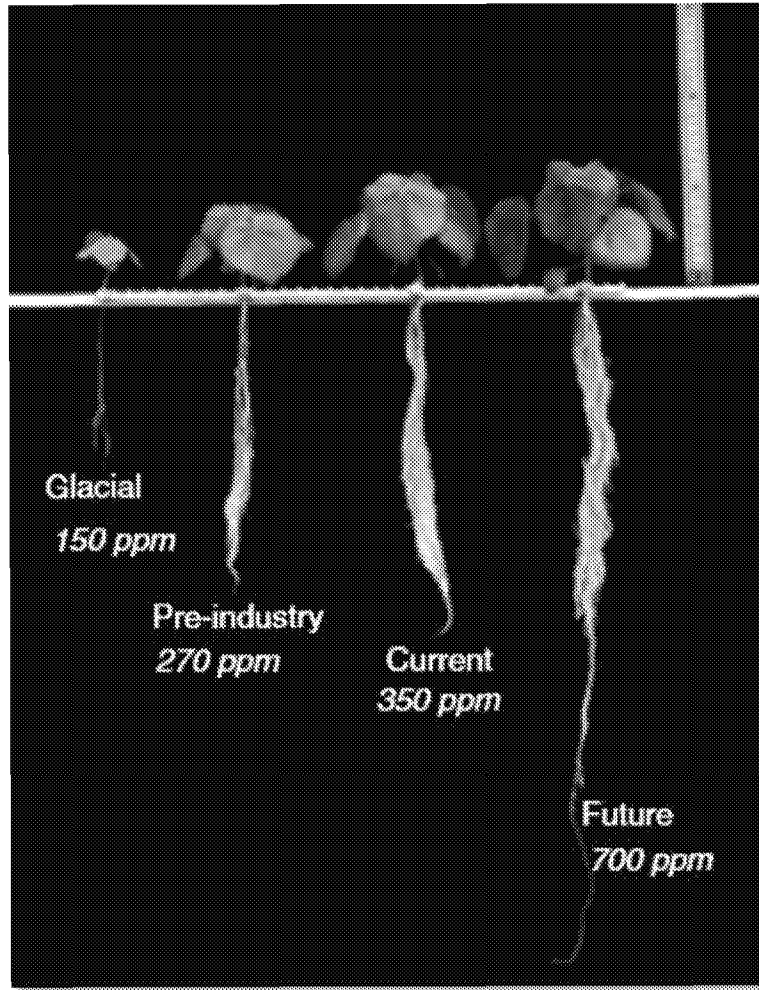


Figure 2.3: growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO₂ levels. Source: Gerhart and Ward (2010). Note “Current” refers to 2010 in image.

Over the past 60+ years there have been thousands of studies on the response of plants to rising CO₂ levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO₂. There are two mechanisms by which CO₂ confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO₂ by opening the stomata (pores) on the leaf surface. When CO₂ is scarce the stomata must be kept wide open for long periods, which allows water to evaporate away. Under enriched CO₂ conditions the stomata are closed for longer periods helping the plant retain water longer, thereby increasing water use efficiency.

Specific effects of climate change on US agriculture will be reviewed in Chapter 10.

2.1.3 Rising CO₂ and crop water use efficiency

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO₂ both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO₂ Enrichment—see Chapter 10) on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO₂ fertilization predicted CWP losses but CO₂ fertilization more than offset them so that all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90% for rice and 60% for maize.

Similarly, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO₂ uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO₂ levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

2.1.4 CO₂ fertilization benefits in IPCC Reports

The IPCC has only minimally discussed global greening and CO₂ fertilization of agricultural crops. The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report entitled “global greening and browning” points out that the IPCC Special Report on Climate Change and Land had concluded with *high confidence* that greening had increased globally over the past 2-3 decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO₂ fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

Overall, however, the Policymaker Summaries, Technical Summaries and Synthesis Reports fail to discuss the topic.

2.2 Ocean Alkalinity

2.2.1 Changing pH

A neutral aqueous solution has a pH of 7.0, while one with pH greater than 7.0 is basic and with pH less than 7.0 is acidic. The modern-day global average pH of sea water is estimated to be 8.04 (Copernicus Marine Service 2025), down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO₂ concentrations in the atmosphere increase, more is absorbed by the oceans, which decreases alkalinity. Depending upon the buffering capacity of the oceans, the oceans are expected to become somewhat less alkaline over time, consistent with the observed decrease in pH.

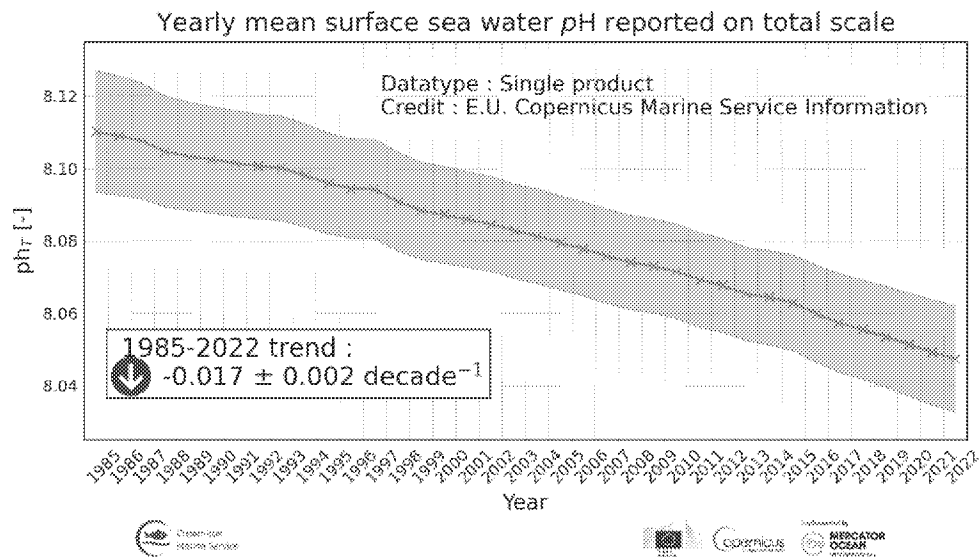


Figure 2.4: Ocean pH 1985 – 2022. Source: Copernicus Marine Service 2025

While this process is often called “ocean acidification”, it is a misnomer because the oceans are not expected to become acidic; “ocean neutralization” would be more accurate. Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 - to 7.0 (Krissansen-Totton et al., 2018). On the time scale of thousands of years, boron isotope proxy measurements of pH show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al., 2018). Thus, there appears to be considerable resilience of ocean biota to natural long-term changes in ocean pH since marine organisms are exposed to wide ranges in pH anyway.

2.2.2 Coral reef changes

There are concerns that a decreasing pH of sea water will reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957). De’ath et al. (2009) reported that a portion of Australia’s Great Barrier Reef (GBR, the world’s largest coral reef ecosystem) had experienced a 14% decline in calcification since 1990. This was tentatively attributed to increasing water temperature and decreasing pH. But Ridd et al. (2013) showed that report to have resulted from a biased data analysis which, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) received by the original study compared to only 11 citations for the correction (as of 30 April 2025).

The most recent annual summary of GBR conditions from the Australian Institute of Marine Science indicates a strong rebound has occurred in coral production (AIMS, 2023). Figure 2.5 shows the results of the AIMS surveys of hard coral cover, expressed as a percentage of the reef area. Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden et al., 2015) as well as a string of marine heatwaves, agricultural runoff and invasive species (Woods Hole, 2023). Given the reported declines in GBR calcification between 1990 and 2009 and the continued increase in atmospheric CO₂ levels the rebound has come as a surprise to some observers.

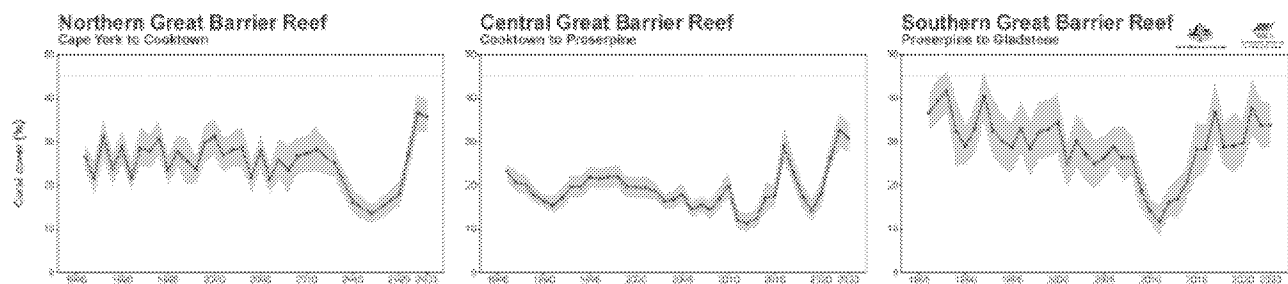


Figure 2.5 Hard coral cover of three regions of the Great Barrier Reef 1985 to 2023. Source: AIMS 2023.

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the impacts of declining ocean pH. An ICES Journal of Marine Science Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, “As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish.” (Browman, 2016).

Similarly, a meta-analysis (Clements et al., 2021) of the negative effects of ocean acidification on reef fish behavior found what they called a “decline effect”: initially dramatic conclusions published in prominent journals showing apparently large reported effects of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to prevent the “decline effect” from persisting:

[The] vast majority of studies with large effect sizes in this field tend to be characterized by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behavior, and we advocate for improved approaches to minimize the potential for a decline effect in future avenues of research (Clements et al., 2022).

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. Much of the public discussion of the effects of ocean “acidification” on marine biota has been one-sided and exaggerated. There is a known tendency for studies reporting dramatic effects on things like coral cover and fish behavior to get published in high-impact journals and receive widespread press coverage, then subsequent research rebutting those findings receives little attention.

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3 HUMAN INFLUENCES ON THE CLIMATE

Chapter Summary

The global climate is naturally variable on all time scales. Anthropogenic CO₂ emissions add to that variability by changing the total radiative balance in the atmosphere.

The IPCC has downplayed the role of the sun in climate change but there are plausible solar irradiance reconstructions that imply it contributed to recent warming.

Climate projections are based on IPCC emission scenarios that have tended to exceed observed trends. The vast majority of academic climate “impacts” studies in recent years are based upon the extreme 8.5 scenario that is now considered implausible; its use as a business-as-usual scenario has been misleading.

Carbon cycle models connect annual emissions to growth in the atmospheric CO₂ stock. Models disagree over the rate of land and ocean CO₂ uptake but all agree that it has been increasing since 1959.

3.1 Components of radiative forcing and their history

3.1.1 Historical radiative forcing

A changing climate has been the norm throughout the Earth’s 4.6-billion-year history. The Earth’s temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing the composition of the atmosphere by emissions of CO₂ and other greenhouse gases and by altering the concentration of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and is cooled by the radiative heat it emits to space. Averaged over the Earth’s surface, each of these processes involve power flows of about 240 Watts per square meter (W/m²). When they are in balance, there are no net external causes of warming or cooling. Both human and natural influences on the climate alter this balance and so cause the climate to change.

Influences on the Earth’s energy balance at the top of the atmosphere are quantified by “radiative forcing”, the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools. The IPCC’s estimated history of major components of radiative forcing since 1750 is shown in the following two figures from its AR6.

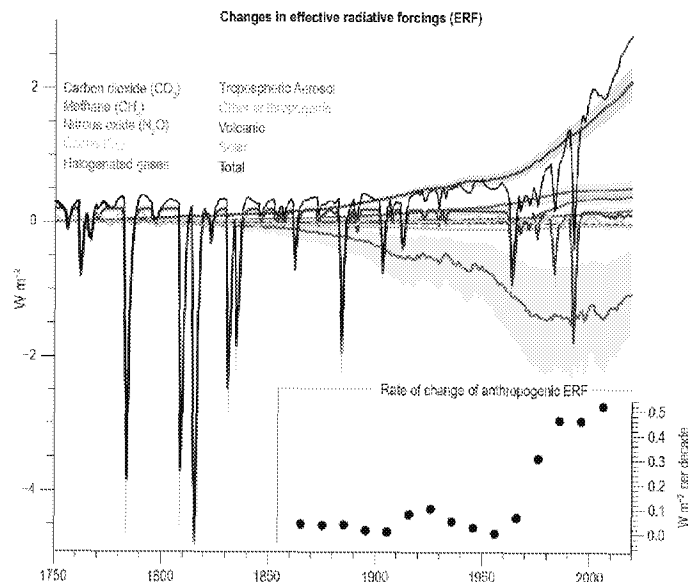


Figure 3.1.1: IPCC estimates of radiative forcing components over time. Source: [[HYPERLINK "https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/"](https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/)]

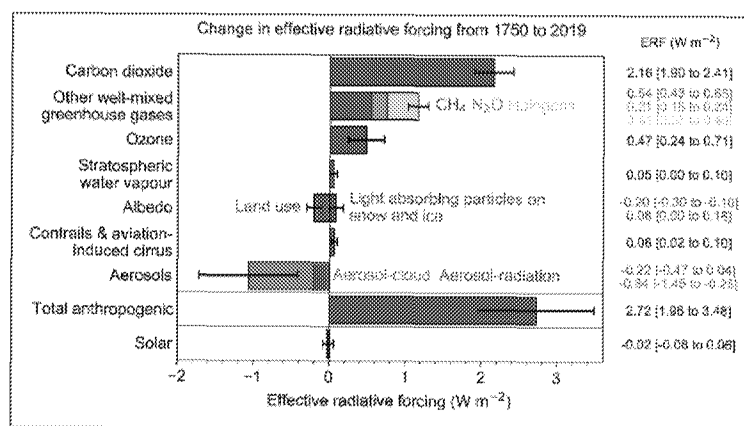


Figure 3.1.2 IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: [[HYPERLINK "https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/"](https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/)]

These graphs show that the total radiative forcing is comprised of both natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the influence of energy systems. It exerts a warming influence by decreasing the cooling power of the atmosphere. Emissions of CO₂ are accumulating in the atmosphere, as described in the following section, so that the warming influence is increasing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone) act similarly, currently adding another 75% to CO₂'s warming. Aerosols exert a cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding the causes of recent warming requires not just identifying the warming effects of CO₂, but also the more uncertain cooling effects of aerosols.

The IPCC views the change in the radiative forcing by the sun to be negligible, based on their preference for reconstructions that imply minimal solar change since preindustrial times. Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature covering the 1600-2000 interval; they vary from almost no change in TSI to a relatively large upward trend. Those authors note that the variation in TSI reconstructions combined with variations in surface temperature reconstructions allows for inferences consistent with either no or most 20th Century warming being attributable to the sun.

A particularly thorny issue is the gap in TSI data between 1989 and 1991 due to a delay in the launch of a monitor following the Space Shuttle Challenger disaster on January 28 1986. That prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system (Zacharias 2014, Scafetta et al. 2019). This is called the ACRIM (Active Cavity Radiometer Irradiance Monitor) gap problem. The question of whether there is an upward trend in TSI over 1978 to 2018 comes down to how the ACRIM data gap is filled. Connolly *et al.* (2023) found that the IPCC's consensus statements on solar forcing were prematurely formulated through the suppression of dissenting scientific opinions.

The other natural radiative forcing component is largely volcanic aerosols, which exert an episodic cooling influence. Box 4.1 in the IPCC AR6 Report addresses the climate impact of volcanic eruptions, noting three explosive volcanic eruptions that occurred in the first half of the 19th century. This included the 1815 Tambora eruption that resulted in the 'year without summer', with multiple harvest failures across the Northern Hemisphere. There is uncertainty about the sign of the relatively small forcing due to the submarine volcano Hunga Tonga which erupted in 2022 (Jenkins et al. 2023, Schoeberl et al. 2024).

The anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m² today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing; state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m². Natural sources of global energy imbalance other than volcanoes and total solar irradiance (TSI) are not included in these graphs because they remain largely unknown.

3.1.2 Change in atmospheric CO₂ since 1958

Carbon dioxide's warming influence depends upon how much "extra" CO₂ accumulates in the atmosphere- *i.e.*, its concentration above the preindustrial value of 280 ppm. The CO₂ level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are available online at [[HYPERLINK "https://gml.noaa.gov/ccgg/trends/index.html"](https://gml.noaa.gov/ccgg/trends/index.html)]. The concentration was about 316 ppm at the start of the record in 1959 and is now about 430 ppm, a 36 percent increase. At the end of the last glaciation CO₂ levels had fallen to about 180 ppm. As discussed in Chapter 2 C3 plants begin dying at CO₂ levels below about 140 ppm and C4 plants at CO₂ levels below 100 ppm, so if CO₂ levels had continued falling plant life might have been in peril.

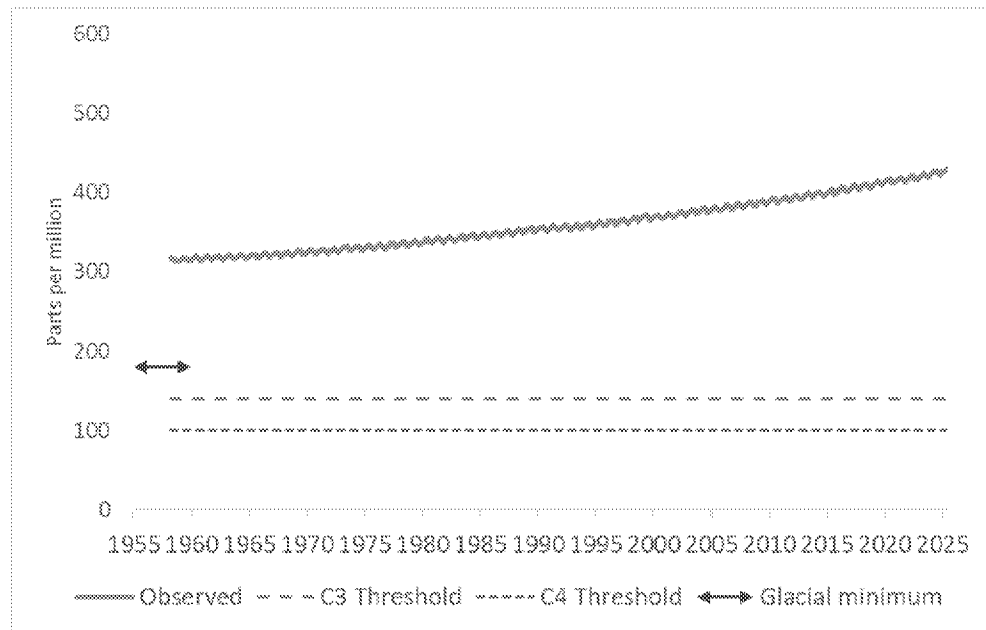


Fig. 3.1.3. CO₂: Yearly average atmospheric CO₂ concentrations (1959-2025) in ppm measured at Mauna Loa (blue). C3 Threshold: Level below which C3 plants begin dying (140 ppm, see Chapter 2). C4 Threshold: Level below which C4 plants begin dying (100 ppm, see Chapter 2). Glacial minimum: Minimum level during recent glaciations (purple arrow). CO₂ data source: [[HYPERLINK "https://gml.noaa.gov/ccgg/trends/index.html"](https://gml.noaa.gov/ccgg/trends/index.html)]

The annual increase in concentration is only about half of the CO₂ emitted because land and ocean processes currently absorb “excess” CO₂ at a rate approximately 50% of the human emissions. Future concentrations, and hence future human influences on the climate, therefore depend upon two components: (1) future rates of global human CO₂ emissions, and (2) how fast the land and ocean remove extra CO₂ from the atmosphere. We discuss each of these in turn.

3.2 Urbanization influence on temperature trends

Historical temperature data over land has been collected mainly where people live. This raises the problem of how to filter out non-climatic warming signals due to Urban Heat Islands (UHI) and other changes to the land surface. If they are not removed the data may over-attribute observed warming to greenhouse gases. The IPCC acknowledges that raw temperature data are contaminated with UHI effects but claims to have data cleaning procedures that remove them. It is an open question whether those procedures suffice for the purpose.

AR6 downplayed the issue by saying (WGI p. 235) that no recent evidence had emerged to alter the AR5 finding that urbanization causes an upward bias of no more than 10% in the global land surface warming trend. AR5 (WGI p. 189) also cited the 10% upper bound without citing a source. AR4 (WGI p. 244) cited Jones et al. (1990) and Peterson et al. (1999) as the basis of the claim. Peterson et al. had failed to find any difference in trends between rural and urban samples, although their definition of rural included local populations up to 10,000 persons and the relative influence of urbanization begins well below that (Spencer et al., 2025). Jones et al. compared rural/urban warming in three regions: Eastern Australia, Eastern China and Western Soviet Union. Their definition of “rural” included towns of up to 10,000 in the

former Soviet Union and up to 100,000 in China. They found relative warming biases greater than 10% in these areas but conjectured that the urbanization effect averaged over the areas they did not examine would bring the global land bias to under 10% of the observed warming trend.

Prior to the IPCC AR4 several papers appeared in print arguing that the warming effect of UHIs added a relatively large (30-50%) component to observed warming and was not simulated by climate models (de Laat and Maurellis 2006, McKittrick and Michaels 2007). These findings were based on correlations between locations of maximum warming over land with locations of maximum socioeconomic development. AR4 asserted (p. 244) that these correlations were an artefact of natural atmospheric circulations and were in fact statistically insignificant, and on that basis set the findings aside. The claim attracted controversy because it was presented with no supporting evidence. McKittrick (2010) ++and McKittrick and Nierenberg (2010) showed that taking into account various conjectured alternative explanations for the correlations did not affect their significance. The AR5 (p. 189) conceded that the AR4 had provided “no explicit evidence” for its assessment and further acknowledged, based on these papers, that there was “significant evidence for such contamination of the record” i.e. a warming bias in the land record. However as noted, elsewhere in the report they carried forward the AR4 claim that it was less than 10% of observed warming and they expressed no caution against using the land record for climate measurement on the assumption that it is not contaminated with UHI bias. Recently Soon et al. (2023) estimated an urbanization bias in the Northern Hemisphere land record over 1850-2018 sufficient to increase the trend in the blended record from 0.55°C to 0.89°C per century.

Some studies providing evidence against UHI contamination compared warming rates between rural and urban locations (Jones et al. 1990, Peterson et al. 1999, Wickham et al. 2013). It is not known whether such methods would be capable of detecting UHI bias even when present. The influence of UHI warming is logarithmic, in other words it is strongest at low population growth levels then tapers off as local urbanization expands (Oke 1973, Spencer et al. 2025). Hence finding the same or more warming in rural areas than in nearby urban areas is consistent either with UHI bias being absent or present. McKittrick (2013) provided an empirical demonstration in which the rural/urban trends were not significantly different in a data set shown on other grounds to be contaminated with UHI bias.

Parker (2006) instead examined a sample of urban locations and found no difference in trends between subsets partitioned according to nighttime wind speed, concluding on this basis that urbanization could not be a significant factor. Here again the question is whether such a method would find UHI bias even if present. McKittrick (2013) presented an example in which UHI-contaminated data did not exhibit significant trend differences when stratified according to wind speed.

The challenge in measuring UHI bias is relating local temperature change to a corresponding change in population or urbanization, rather than to a static classification variable such as rural or urban. Spencer et al. (2025) use newly-available historical population archives to undertake such an analyses and found evidence of significant UHI bias in US summertime temperature data.

In summary while there is clearly warming in the land record, there is also evidence that it is biased upward by patterns of urbanization and that these biases are not removed by the data processing algorithms used to produce climate data sets.

3.3 Future emission scenarios and the carbon cycle

3.3.1 Emission scenarios

Because of the great uncertainties about these many factors in the decades to come, Assessing the dangers of future GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic

activity, regulation, and energy and agricultural technologies. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Instead of making precise predictions of future concentrations, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, and technologies. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m² of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m².)

Although the IPCC does not claim its emission scenarios are forecasts, they are often treated as such. Comparisons of past scenario groups against observations show a tendency for IPCC emission projections to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* was used; these were referred to as the SREP scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita values, the SREP scenario emissions distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO₂ emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis of Hausfather *et al.* (2019) who showed that observed atmospheric CO₂ concentrations tracked the low end of the SRES range and also of subsequent IPCC scenario ranges.

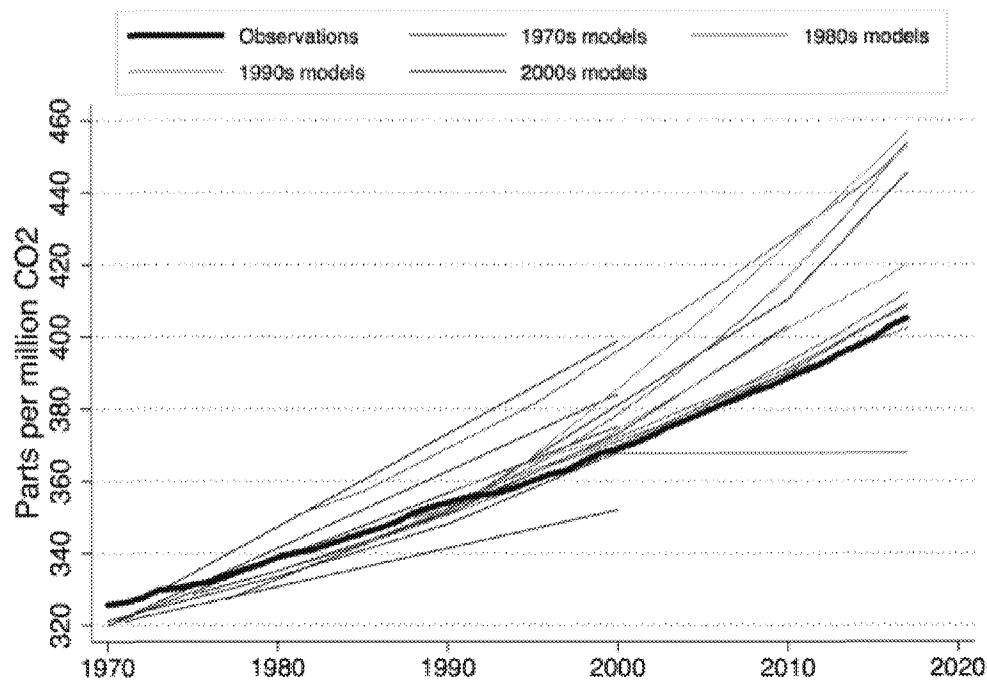


Figure 3.3.1 Comparison of observed atmospheric CO₂ levels (black line) with scenario projections (colored lines, mainly IPCC) since the 1970s. Source: Hausfather *et al.* (2019) Figure S4.

For AR5 the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCPs). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying an anthropogenic radiative forcing in 2100 of 2.6 W/m²) projects a GHG concentration pathway leading to warming well below 2°C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5°C warming just in this century.

RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21st century world in the absence of increasingly stringent emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its use as a business-as-usual baseline has been criticized as grossly misleading.¹ Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as an extreme worst-case, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting.

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed trends in energy use and the near future trends diverge sharply from those of the International Energy Agency (IEA), which provides market-based projections of energy use for the coming decades. The IEA trends, which are based on plausible extrapolations of current economic and demographic trends, run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but that even lower emission scenarios are looking unlikely.

Widespread use of RCP8.5 has created an alarmist bias in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles linking RCP8.5 to the concept of “business-as-usual”. Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets.

Pielke and Ritchie (2020) reported new studies using RCP8.5 were published at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude that the climate research community has spent a decade “committing scientific resources to science fiction” and that “The scientific literature has become imbalanced in an apocalyptic direction.”

The IPCC developed a new set of scenarios for AR6, the “Shared Socioeconomic Pathway” (SSP) scenarios, which have continued the bias shown in the RCP and SRES scenarios. Figure 3.3.2 shows total global observed CO₂ emissions compiled by the International Energy Agency (IEA) merged with the emission projection from the EIA taking account of energy use projections and current policies. The other lines show the range of IPCC SSP scenarios (SSP1-SSP5). As of 2023, global CO₂ emissions have been tracking well below SSP3 and higher.

¹ This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model’s sensitivity. But that’s very different than claiming it is a plausible future.

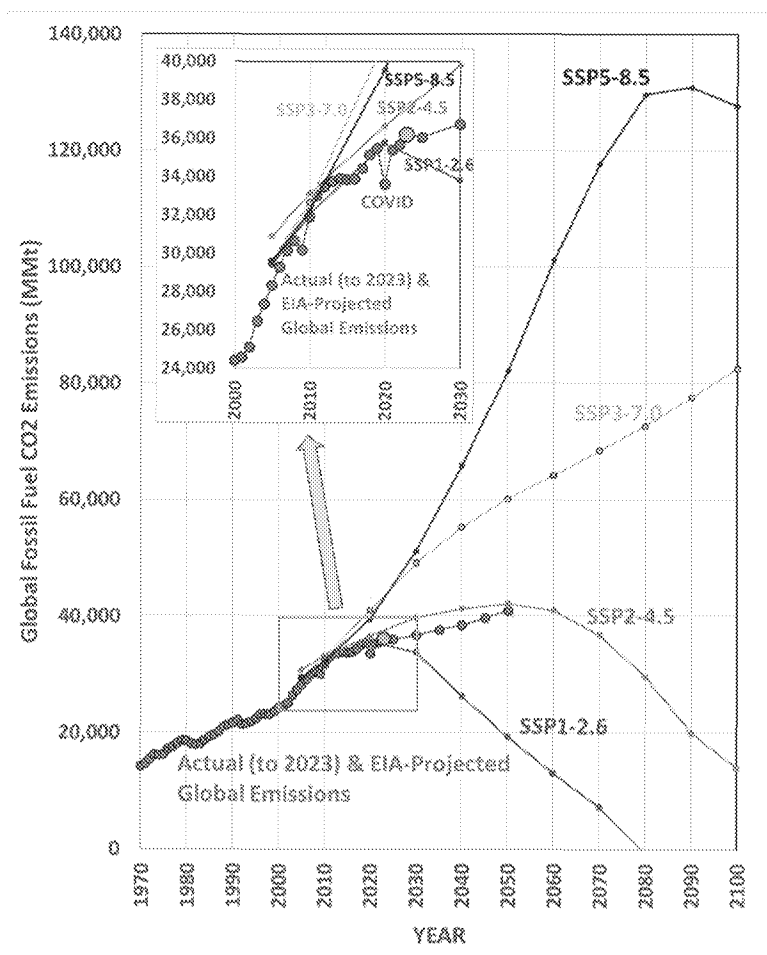


Figure 3.3.2. Observed and projected CO₂ emissions. Source: IPCC (SSP scenarios) and Energy Information Administration (EIA). Green: observed historical emissions and EIA projections. Other lines: SSP1-5. Data source: Friedlingstein et al. (2024).

3.3.2 The carbon cycle relating emissions and concentrations

Carbon dioxide emissions from fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) have led to steadily increasing CO₂ concentrations in the atmosphere, as shown in Fig. 3.1.3. The relation between emissions and concentration is determined by the global carbon cycle of land and ocean processes that exchange carbon with the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021).

There are about 850 Gt of carbon (GtC) in the Earth's atmosphere², almost all of it in the form of CO₂. Each year, biological processes (plant growth and decay) and physical processes (ocean absorption and outgassing) exchange about 200 GtC of that carbon with the Earth's surface (roughly 80 GtC with the land and 120 GtC with the oceans). Before human activities became significant, removals from the atmosphere

² Because CO₂ is chemically transformed through the course of the carbon cycle, it is more convenient to track atoms of carbon rather than molecules of CO₂. One gigatonne of carbon (GtC) is equivalent to about 3.7 Gt of CO₂.

were roughly in balance with additions. But burning fossil fuels (coal, oil, and gas) takes carbon out of the ground and adds it to the annual exchange. That addition (together with a much smaller contribution from cement manufacturing) amounted to 10.3 GtC in 2023, or only about 5 percent of the annual exchange.

The carbon cycle accommodates about 50 percent of humanity’s small annual injection of carbon into the air by naturally sequestering it through plant growth and oceanic uptake, while the remainder accumulates in the atmosphere (Ciais et al., 2013). For that reason, the annual increase in atmospheric CO₂ concentration averages only about half of that naively expected from human emissions.

To project future CO₂ concentrations in the atmosphere, and hence future human influences on the climate, it is important to know how the carbon cycle might change in the future. The historical near-constancy of that 50% fraction means that the more CO₂ humanity has produced, the faster nature removed it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO₂ after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes that remove excess CO₂ from the atmosphere are increased growth of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO₂ by the ocean due to the increasing partial pressure of atmospheric CO₂ over that of CO₂ dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO₂ at an increasing rate since 1959. This is consistent with a “global greening” phenomenon (Chapter 2.1) observed by satellites since monitoring of global greenness began in the 1982.

While land vegetation has been responding positively to more atmospheric CO₂, uptake of extra CO₂ by ocean biological processes remains too uncertain to be measured reliably. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp *et al.* (2021).

CO₂ uptake by land processes

The uptake of extra CO₂ from the atmosphere by land surface processes (as also inferred from global greening) has been modeled with 20 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). As seen in Fig. 3.3.3, all of those models agree that vegetation and soils have been sequestering carbon from the atmosphere. But we also see that the long-term trends over 1959 to 2023 (65 years) vary widely between models, by nearly a factor of 7. This demonstrates that there remains considerable uncertainty regarding how fast CO₂ from the atmosphere is being removed by land processes, which in turn translates into uncertainty regarding future atmospheric CO₂ concentrations. Those uncertain future CO₂ concentrations then imply a source of uncertainty in climate model simulations of future climate change.

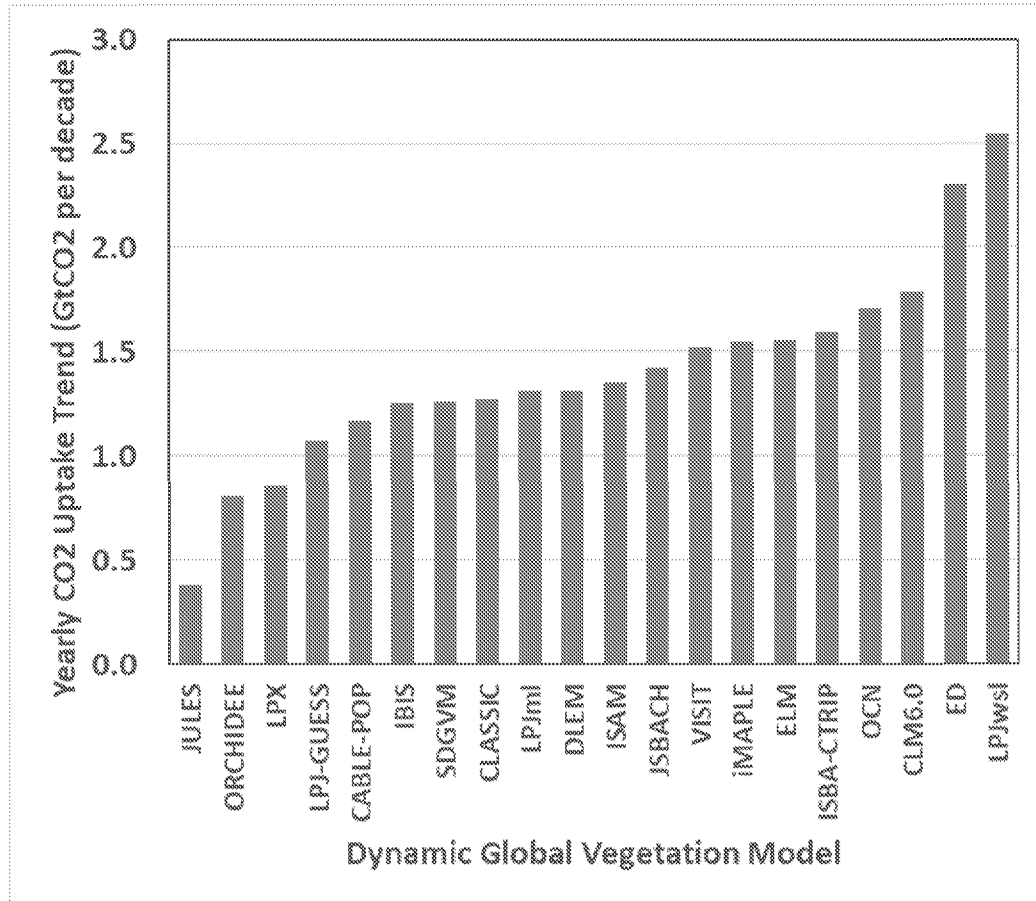


Figure 3.3.3 Decadal trends in the yearly CO₂ uptake by land processes during 1959-2023 simulated by 20 different dynamic global vegetation models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

CO₂ uptake by ocean processes

The uptake of extra CO₂ from the atmosphere by ocean processes has been modeled with 10 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). Like the results from the land models, all of the ocean models agree that the global oceans have been sequestering carbon from the atmosphere at an increasing rate during 1959-2023 (Fig. 3.3.4). Unlike the land models, however, the ocean models show much better agreement with each other, with the model producing the fastest increasing CO₂ uptake being only 65% faster than the model with the most slowly increasing CO₂ uptake. Note that the average trend in CO₂ uptake across all land models in Fig. 3.3.3 is 25% larger than the average trend in ocean uptake. This suggests land processes are increasing in their ability to remove CO₂ faster than ocean processes are increasing their CO₂ sequestration.

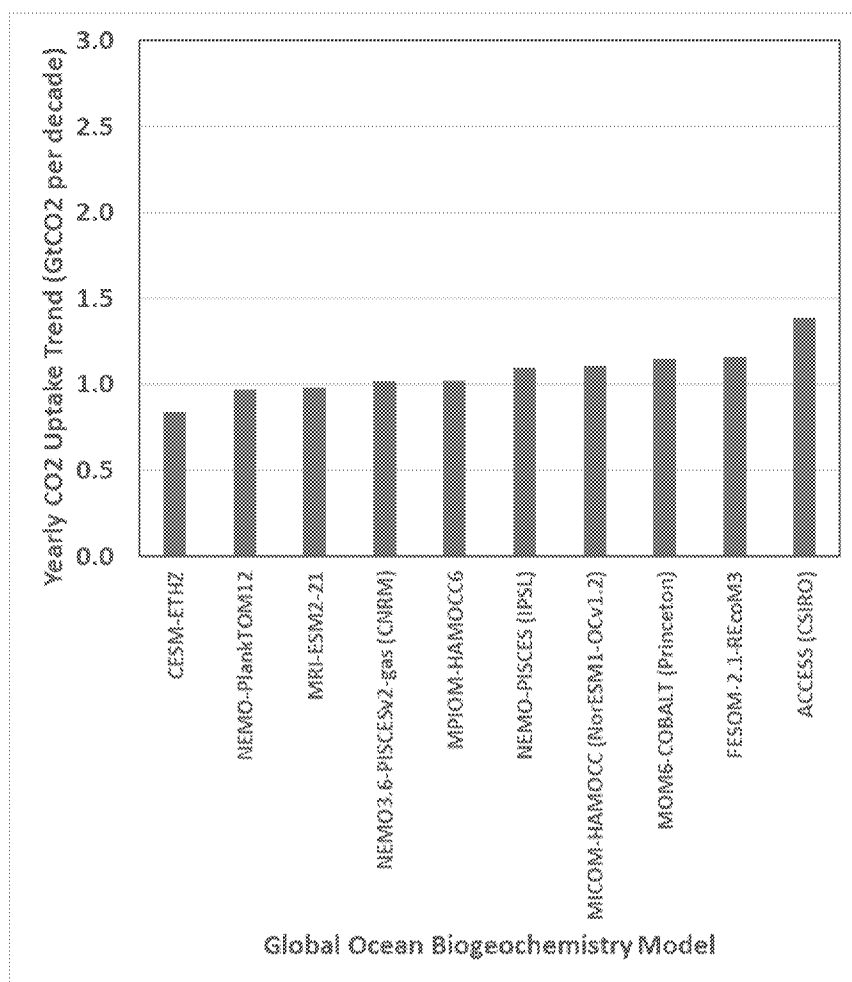


Figure 3.3.5 Decadal trends in the yearly CO₂ uptake by ocean processes during 1959-2023 simulated by 10 different ocean biogeochemistry models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

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PART II: CLIMATE RESPONSE TO CO₂ EMISSIONS

4 CLIMATE SENSITIVITY TO CO₂ FORCING

Chapter Summary

There is growing recognition that climate models are not fit for the purpose of determining the Equilibrium Climate Sensitivity (ECS) of the climate to increasing CO₂. The IPCC has turned to data-driven approaches using historical data and paleoclimate reconstructions, but their reliability is diminished by data inadequacies.

Data-driven ECS estimates tend to be lower than climate model-generated values. The IPCC AR6 upper bound for the likely range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by paleoclimatic data. The IPCC AR6 lower bound for the likely range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound is more weakly justified. Evidence since the AR6 finds the lower bound of the likely range to be around 1.8°C.

4.1 Introduction

The climate's response to increasing concentrations of CO₂ is central to the scientific debate on anthropogenic climate change, and so also to the public debate on “climate action.” The simplest measure of that response is the rise in the global average surface temperature, quantified by the Equilibrium Climate Sensitivity (ECS). ECS is defined as the amount of warming expected in response to a doubling of CO₂ from its pre-industrial concentration of 280 ppm, after all climate components have had time to adjust. Some components, like temperatures in the lower atmosphere (troposphere), adjust rapidly, while others such as the deep ocean and cryosphere might take as long as centuries. A related measure, the Transient Climate Response (TCR), better describes the shorter time scales; it is defined as the amount of warming when the CO₂ concentration is doubled by rising one percent annually for 70 years.

The 1979 Charney Report for the US National Academy of Sciences (Charney *et al.* 1979) proposed that the most likely ECS was $3.0 \pm 1.5^\circ\text{C}$. The IPCC repeatedly reaffirmed that range with only minor variations until its most recent AR6. AR5 termed 1.5–4.5°C as the *likely* range (66 percent probability) and stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C.

The uncertainty in ECS has remained stubbornly wide, despite many individual studies that claimed to narrow it. Most recently, AR6 narrowed the *likely* range to 2.5–4.0°C and deemed the *very likely* range to be 2.0–5.0°C. This narrowing on the low end is disputed, as will be discussed below.

Uncertainties in ECS are highly consequential for policy making. As will be discussed in Chapter 11, economic models use ECS values to project the costs of CO₂ emissions. The traditional value (3.0 °C) has typically yielded modest global social costs of CO₂ emissions, sufficient to justify some policy actions, but mostly deferred to later in this century. If ECS is very high (above 4.5°C) immediate aggressive emission controls become more imperative, whereas no CO₂ emission controls are economically justifiable for ECS below 2.0°C (Dayaratna et al. 2016, 2020). Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

4.2 Model-based estimates of climate sensitivity

The ECS ranges given in IPCC AR4 and AR5 were obtained primarily by examining the behaviour of large-scale climate models, also called General Circulation Models (GCMs). However, the IPCC changed course in its AR6 when it turned to a more direct data-driven methodology. Here we discuss some of the pitfalls of using GCMs to try to determine the Earth's climate sensitivity.

ECS is an emergent property of climate models—that is, it is not directly parameterized or tuned. Historically, collections of parameterizations have been chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes, particularly in AR4 and to a lesser extent in AR5. Otherwise plausible GCMs and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model’s climate sensitivity being outside an accepted range. For example, even in a CMIP6 model, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model (emphasis added):

“We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, as opposed to tuning the aerosol forcing.”

In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

Direct warming from CO₂ doubling is only about 1°C (Hall and Manabe 1997); further warming arises from climate feedbacks that are not explicitly resolved by the GCM but rely on parameterizations of physical processes. Higher values of ECS arise primarily from assumed positive cloud feedbacks, whereas the magnitude and even the sign of the feedbacks are very uncertain. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for GCMs to simulate any of these processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

ECS can be determined from climate model simulations by doubling the concentration of CO₂ and allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, “effective climate sensitivity” is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO₂.

The spread of ECS values from the CMIP5 ensemble of climate models used in the AR5 was 2.0–4.7°C; that range increased for the CMIP6 models used in the AR6 to between 1.8 and 5.7°C (Chen et al., 2021, Scaffeta 2021, see Figure 5.1). Far from settling the model-based sensitivity of climate system uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models (Zelinka et al., 2020)

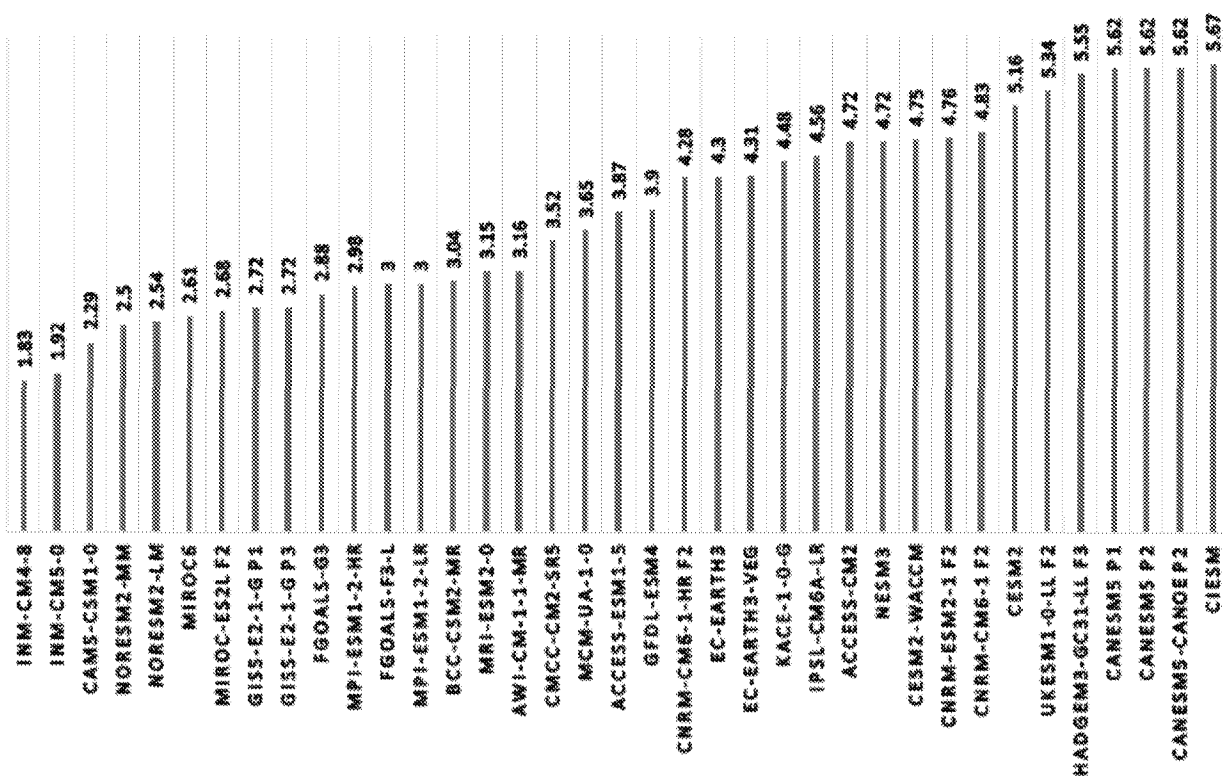


Figure 4.1 Equilibrium Climate Sensitivities in °C of 37 climate models from the CMIP6 ensemble. Identifiers for the various models appear along the horizontal axis. From (Scafetta, 2021) <https://www.mdpi.com/2225-1154/9/11/161>

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6(2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on other methods, chiefly a recent empirical estimate.

4.3 Data-driven estimates of climate sensitivity

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past (Otto et al., 2013). Using this information, a simple empirical model called an Energy Balance Model can be employed. It requires estimating a feedback parameter whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007).

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al., 2007). Observed 20th century warming can be shown to be consistent either with low ECS and low aerosol cooling, or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO₂. Over time, the IPCC's estimate of the cooling effect of aerosols has declined (Lewis, 2022).

Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth’s temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data are smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates based on historical data appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For the AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical and paleoclimate proxies and yielded a best estimate of 3.1°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis’ analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent *likely* range, and 1.6–3.2°C in the 5–95 percent *very likely* range). The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

An argument emphasized in AR6 is that data-driven ECS estimates might understate the future warming response to GHGs because of a so-called “pattern effect” (Forster et al., 2021). The tropical Pacific is believed to strongly influence the overall efficiency with which the Earth radiates heat to space, but some regions remove heat more efficiently than others. If the west-to-east temperature gradient in the tropical Pacific is weakened in a warming climate, warming would concentrate where heat is less efficiently removed, raising ECS.

Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value. However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere”; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be *lower* than current estimates.

4.4 Transient Climate Response

The Transient Climate Response (TCR) provides a more useful observational constraint on climate sensitivity. TCR is the amount of warming that results when CO₂ is increased at an annual rate of 1 percent over a period of 70 years (i.e., doubled gradually). Relative to the ECS, observationally determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS.

IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. In contrast to ECS, the upper bound of TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) are 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

As will be discussed in Chapter 6, a real-world ECS smaller than the model average is supported by studies that show climate models on average overestimate the observed surface and troposphere warming over the past 50 years. Lower sensitivities also align with evidence from consistent fingerprinting (Section 8), where model responses need to be downscaled to align with observed trends.

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5 MODELS VERSUS OBSERVATIONS IN THE RECENT PAST

Chapter summary

Climate models show warming biases in many aspects of their reproduction of the past few decades. In response to observed changes in forcing inputs they produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft.

Climate models also produce too much recent stratospheric cooling, too much water vapor increase, too much snow loss, and too much warming in the corn belt. The IPCC has acknowledged some of these issues but not all.

5.1 Introduction

Climate models are the primary tool used to project future climate changes in response to increasing atmospheric levels of anthropogenic greenhouse gases. They provide theoretical evidence underpinning energy policy changes, such as efforts to reduce carbon dioxide emissions. To assess the fitness of climate models for this purpose, it is reasonable to ask how well they reproduce the current climate and its variations over the past century. The nearby box “Climate modeling” gives some detail on how climate models work.

Of great concern is the fact that, after several decades of the climate modeling enterprise involving approximately three dozen models operated by research centers around the world, the range of future warming they produce in response to a hypothetical doubling of atmospheric CO₂ extends over a factor of three, as we discussed in the previous chapter. This range of disagreement among models has not changed for decades.

Problems with climate models are not just in their disagreement over the future, but also in their ability to replicate the recent past. Here we review some of the most important metrics of climate model accuracy: ability to reproduce historical surface, tropospheric and stratospheric temperature trends, ability to reproduce the vertical warming profile and ability to reproduce other climate features such as snowfall and humidity. In all cases a persistent finding is that models on average err on the side of too much warming in response to observed historical forcings.

Box: Climate modeling

Most climate models, except for the simplest ones, represent Earth's land surface using a grid of squares, typically 100 km wide. To simulate the atmosphere, 10 to 20 layers of grid boxes are stacked above these squares. The ocean is modeled using a similar but finer grid, resulting in approximately one million grid boxes for the atmosphere and 100 million for the ocean.

The computer models, based on physical laws, calculate how air, water, and energy move between grid boxes over time. The time step can be as small as 10 minutes, and repeating this process millions of times allows the simulation of climate over centuries. Running these models, even on the most powerful supercomputers, can take months. Comparing simulation results with historical climate data helps assess the accuracy of a model, while projections into the future estimate climate changes under assumed human and natural influences.

Despite sounding straightforward, climate modeling is highly complex. Many critical processes occur at scales smaller than the 100 km grid size. For instance, the flows of sunlight and heat in the atmosphere depend strongly on cloud cover. Since tracking individual clouds is impractical, researchers must make "subgrid" assumptions about the distribution of clouds in each grid box. Snow and ice cover, which affects how much sunlight is reflected or absorbed by the surface, is another subgrid factor.

Each subgrid assumption requires numerical parameters, which must be carefully set. Modelers initially estimate these parameters based on physics and observed climate patterns, then run the model. Because early results often diverge significantly from real-world observations, they "tune" these parameters to better match observed climate features. Different modeling teams use distinct assumptions and tuning strategies, leading to varied outcomes. Tuning is a necessary but delicate aspect of climate modeling, as it is in any complex system. Poor tuning can result in inaccurate simulations, while excessive tuning risks artificially steering results toward predetermined conclusions.

To distill useful insights from these varied models, climate studies often rely on averaged results from multiple models, forming an "ensemble." The latest UN IPCC assessments use the CMIP6 ensemble, which shows a significant diversity of results. One of the most basic climate indicators—the Earth's average surface temperature—varies by about 3°C across the ensemble, three times greater than observed warming during the 20th century.

Although model success in reproducing some features of today's climate is reassuring, the critical issue for society is how well they predict responses to subtle human influences, such as greenhouse gas emissions, aerosol cooling, and land-use changes. The most crucial aspect models must capture correctly is "feedbacks." These occur when climate changes triggered by greenhouse gases either amplify or suppress further warming. For example, as global temperatures rise, snow and ice melt, reducing Earth's reflectivity. With less reflective surfaces, the planet absorbs more sunlight, leading to additional warming. Other significant feedbacks involve water vapor levels, cloud formation, and atmospheric temperature profiles. Based on ensemble averages, the net effect of all feedbacks is estimated to double or triple the direct warming impact of CO₂.

5.2 Surface warming

A straightforward test of a climate model's validity is its ability to reproduce historical warming in response to known past changes in climate drivers such as greenhouse gases. Figure 5.2 is reproduced from Scaffeta (2023), a peer-reviewed study that groups the latest-generation (CMIP6) climate models into low ECS (1.5 to 3.0 degrees C), medium ECS (3.0 to 4.5 degrees C) and high ECS (4.5 to 6.0 degrees C), and compares their post-1980 global average temperature simulation ranges to those of three surface temperature records and one satellite-based lower troposphere temperature data product.

The leftmost column shows that the low-ECS models track the post-1980 historical warming record reasonably well, but the middle and right columns show that the medium- and high-ECS models conspicuously over-predict the warming.

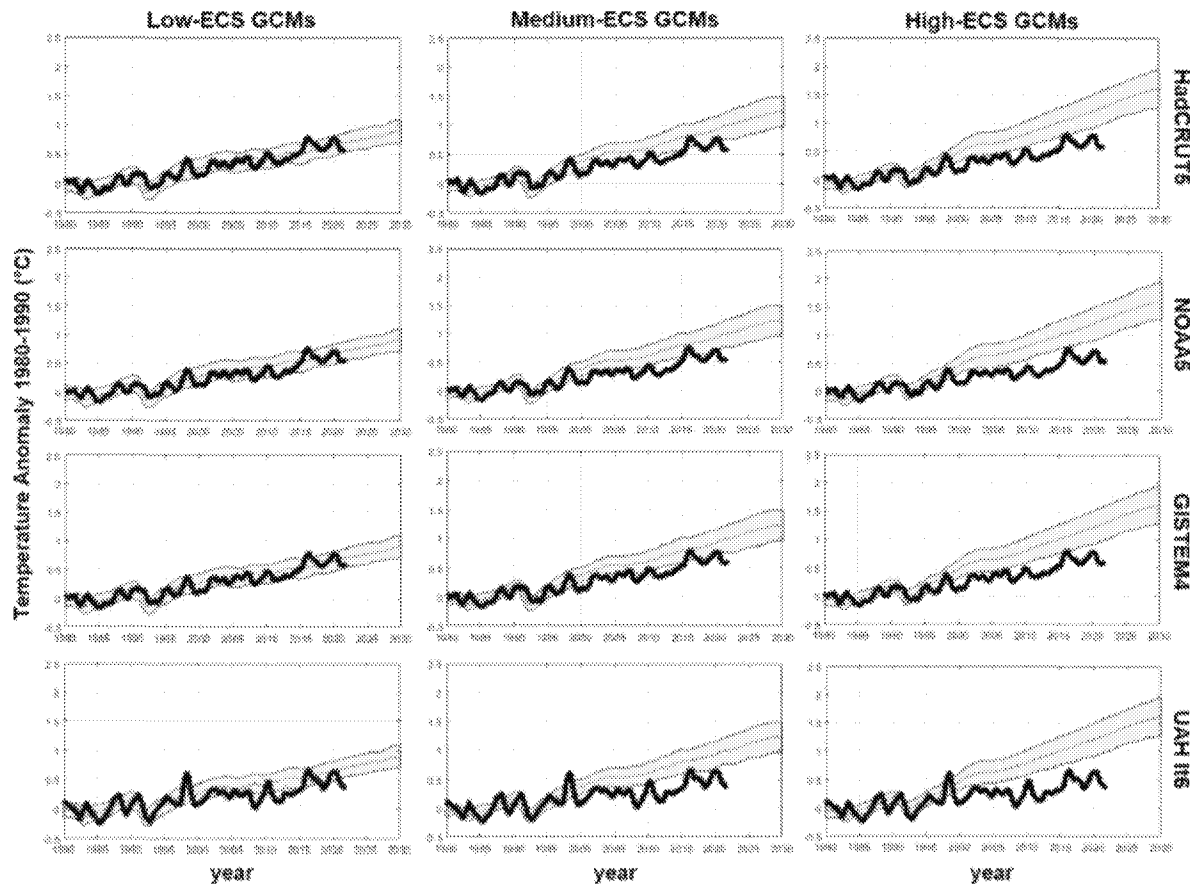


Figure 5.2: model-observational comparisons for Earth’s surface warming. The columns correspond to model groups showing low-ECS to high-ECS, while the rows correspond to widely-used observed temperature records, the first three showing surface averages and the fourth showing the lower troposphere average. In each panel the yellow area denotes the mean and range ($\pm$ one standard deviation) of climate model simulations for that group. The thick black line shows the observed annual average temperature in the indicated source. Source: Scafetta N. Climate Dynamics 2023 Fig.2.

Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by comparing trends in surface temperature data products with those in individual climate models, as summarized in Figure 5.3.

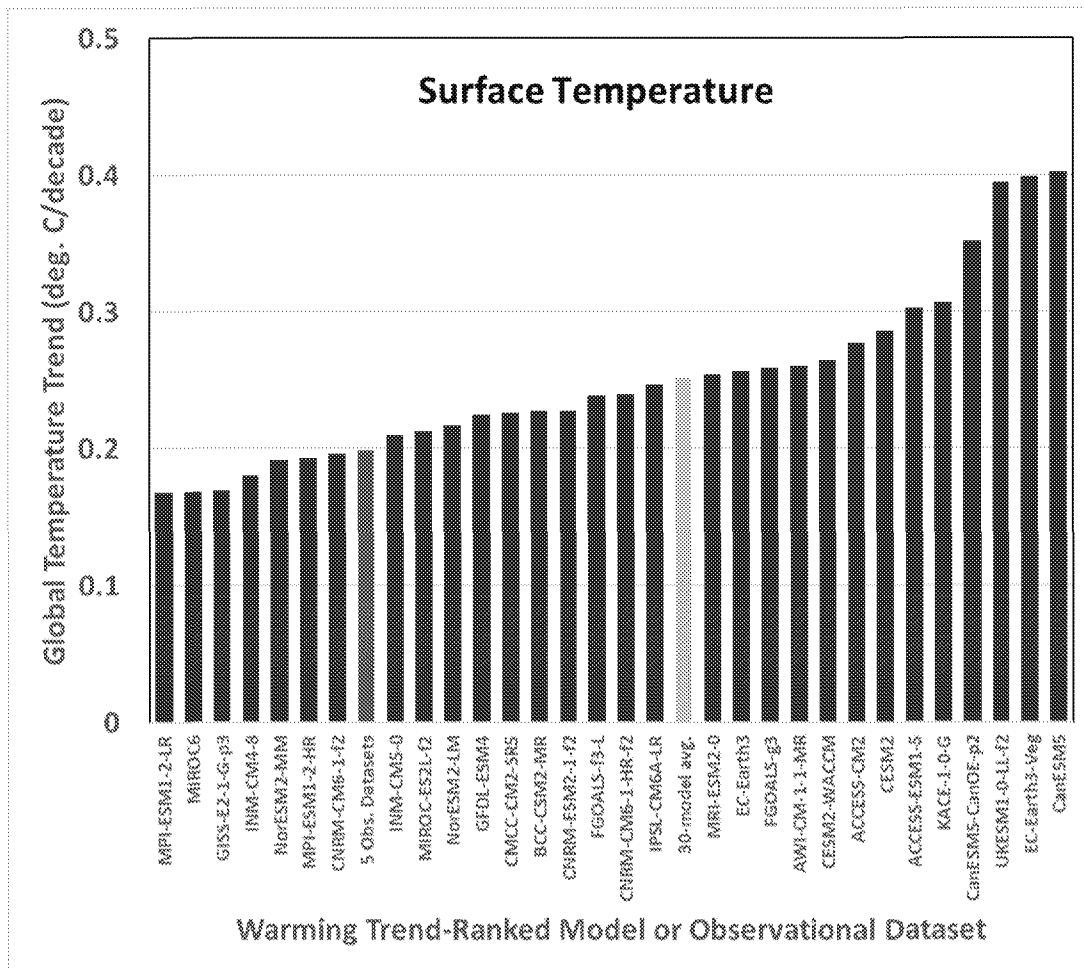


Figure 5.3 Global surface air temperature trends ($^{\circ}\text{C}/\text{decade}$), 1979-2024, from various CMIP6 climate models (red, 30-model average in orange); and the average of three thermometer datasets (HadCRUT5, NOAA Global Temp, and Berkeley 1 deg.) and two reanalysis datasets (ERA5 and NCEP/NCAR R1) in blue.. Source: Spencer (2024) updated

5.3 Tropospheric warming

It has long been known that climate models on average overstate warming in the tropical troposphere. This region is an important test of the models since it has long been hypothesized that this is where the signal of anthropogenic greenhouse warming emerges first and most strongly. Biases in tropospheric trends indicate model flaws in heat transfer processes and carry over to surface warming biases.

The discrepancy was flagged as a serious inconsistency in the first US Climate Change Science Program report (Karl et al. 2006) and has been mentioned in every IPCC report since, but it has gotten worse over time, and the bias is now global. McKittrick and Christy (2020) compare tropospheric warming trends in CMIP6 climate models to observed trends from satellites, weather balloons and reanalysis systems. Figure 5.4 presents the comparisons with data updated to 2024. Every model overpredicts the average observed warming trend in both Lower- and Mid-Troposphere layers, both globally and in the tropics. In most individual models the bias is statistically significant and on average across models it is highly significant. McKittrick and Christy (2020) also show that the bias is larger in high-ECS models, but

even the models with lower average ECS predict too much warming. If future climate models were to realistically represent global tropospheric warming, they would likely be less sensitive than even the low-ECS members of the CMIP6 ensemble

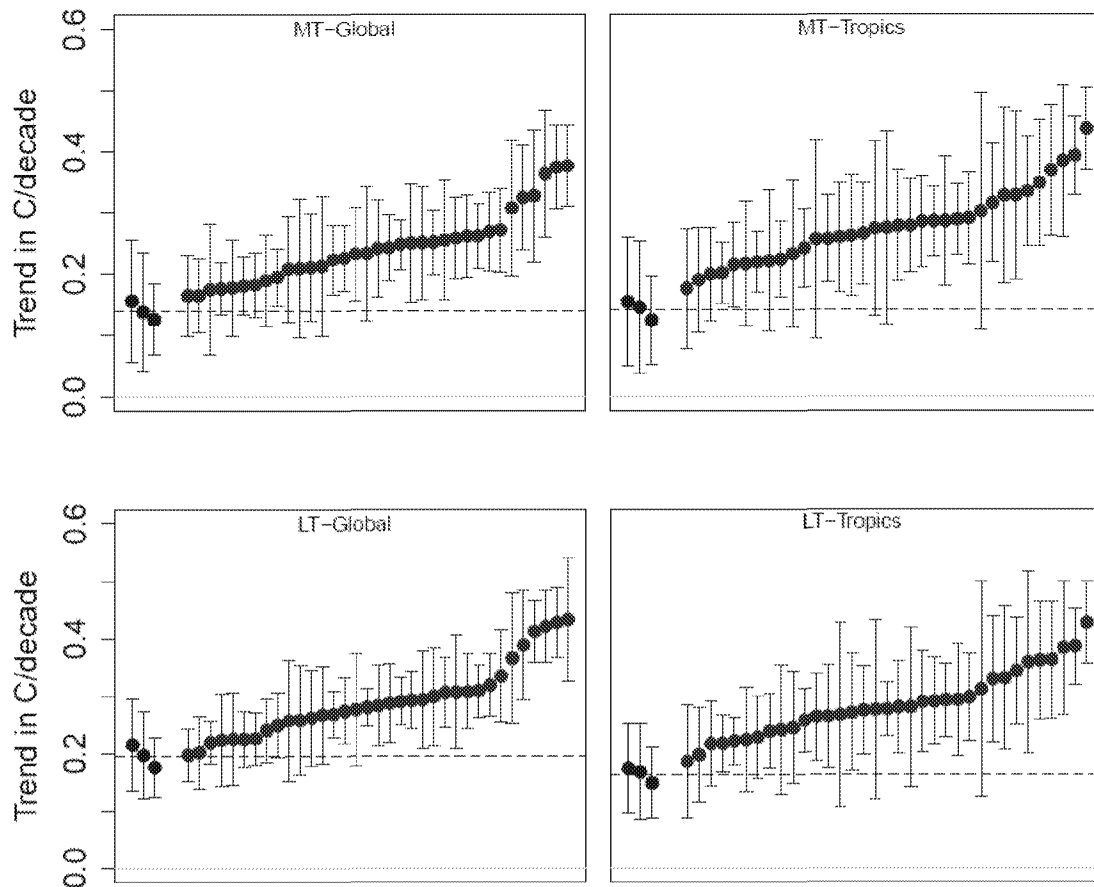


Figure 5.4: Observed versus CMIP6 modeled warming trends ($^{\circ}\text{C}/\text{decade}$ 1979-2024) in the global and tropical lower (LT) and mid-troposphere (MT). Uses methodology of McKittrick and Christy (2020) on updated data. Blue dots: warming trends with 95% confidence interval bars for 3 data products (radiosondes, reanalysis and satellites) and 95% confidence interval bars. Blue dashed line: warming trend average for 3 observed series. Red dots: modeled warming trends in 35 models arranged lowest to highest.

As mentioned the IPCC has long acknowledged the model-observation mismatch. For example AR6 pp. 443-444 offers this on the tropical troposphere (it does not address the global comparison):

Several studies since AR5 have continued to demonstrate an inconsistency between simulated and observed temperature trends in the tropical troposphere, with models simulating more warming than observations (Mitchell et al., 2013, 2020; Santer et al., 2017a, b; McKittrick and Christy, 2018; Po-Chedley et al., 2021)... Over the 1979–2014 period, models are more consistent with observations in the lower troposphere, and least consistent in the upper troposphere around 200 hPa, where biases exceed 0.1°C per decade. Several studies using CMIP6 models suggest that

differences in climate sensitivity may be an important factor contributing to the discrepancy between the simulated and observed tropospheric temperature trends (McKittrick and Christy, 2020; Po-Chedley et al., 2021), though it is difficult to deconvolve the influence of climate sensitivity, changes in aerosol forcing and internal variability in contributing to tropospheric warming biases (Po-Chedley et al., 2021). Another study found that the absence of a hypothesized negative tropical cloud feedback could explain half of the upper troposphere warming bias in one model (Mauritsen and Stevens, 2015).

... In summary, studies continue to find that CMIP5 and CMIP6 model simulations warm more than observations in the tropical mid- and upper-troposphere over the 1979–2014 period (Mitchell et al., 2013, 2020; Santer et al., 2017a, b; Suárez-Gutiérrez et al., 2017; McKittrick and Christy, 2018), and that overestimated surface warming is partially responsible (Mitchell et al., 2013; Po-Chedley et al., 2021). Hence, we assess with *medium confidence* that CMIP5 and CMIP6 models continue to overestimate observed warming in the upper tropical troposphere over the 1979–2014 period by at least 0.1°C per decade,

Notably, despite the accumulation of evidence of excess model warming the IPCC only assigns *medium confidence* to the existence of a warming bias.

5.4 Vertical profile mismatch and excess amplification

Another important model-observational discrepancy is the excess amplification with altitude found in climate models. The comparison was in the IPCC AR5 Chapter 10, although only in the online supplement (Figure 10.SM.1) and only in a figure the formatting of which made the point difficult to see. Figure 10.SM.1 is not referenced in the main IPCC report nor in any summary so readers would not have been aware of it. Although not apparent at first glance, it shows that the 1979-2010 warming in the lower troposphere is so small as to be consistent with no GHG forcing at all, and is inconsistent with the model runs that do have GHG forcing. In Figure 5.6 we adapt IPCC AR5 Figure 10.SM.1 to draw out the critical point.

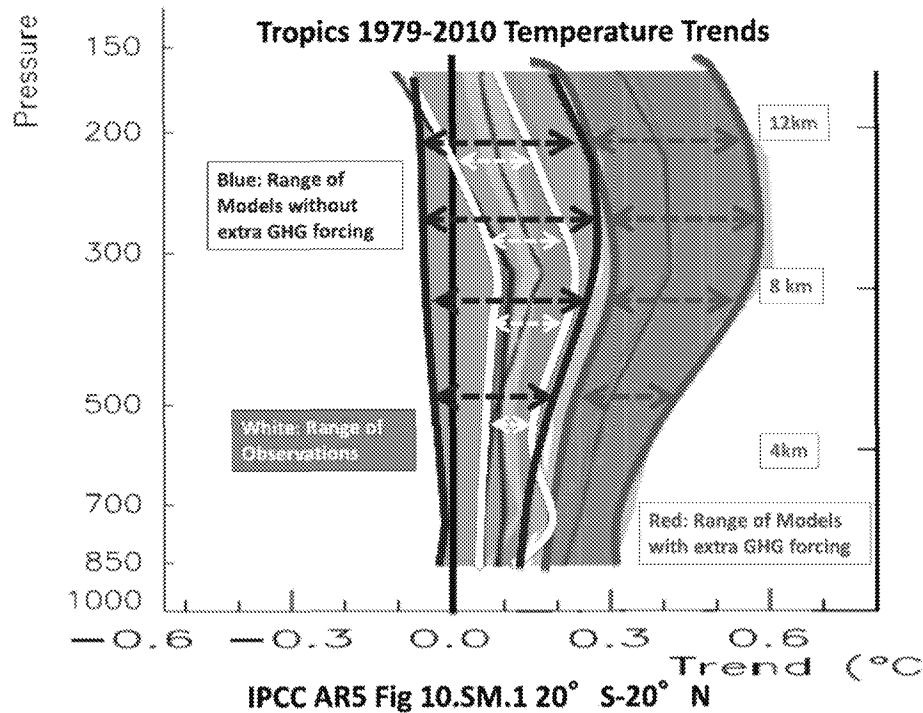


Figure 5.6: Vertical warming pattern for tropics (20S to 20N). Source: Annotated version of IPCC AR5 Figure 10.SM.1

Figure 5.6 compares temperature trends by altitude between models and observations between 20S and 20N (the tropics). In this region where the models say the warming should be strongest, the observations (shown here in white) lie within the “No CO₂” band and entirely outside the “with CO₂” red envelope. This means that in the entire tropical atmospheric column from the surface to the stratosphere, *observed warming trends are so small they are consistent with the output of models that have no CO₂ warming effect in them, and they are inconsistent with the entire envelope of warming trends generated by models forced with increased CO₂.*

A similar comparison is shown in Christy and McNider (2017), an updated version of which (covering 1979-2024) is reproduced as Figure 5.7. Modeled temperature trends exceed observations from the surface through the top of the troposphere, with observed trends below the entire model range at most pressure levels. Also shown in Figure 5.7 is the tropical tropospheric temperature (TTT) average from three satellite data products (NOAA, UAH and RSS) compared to the same layer average from climate models for 1979-2024. Again the observed trends lie below the entire model range.

The wide range of choices made by modelers to characterize the physical processes in the models (see Box: Climate Modeling in Section 5.1 above) is seen by the large spread of trends in the middle troposphere where values range over $\pm 40\%$ from the median value (Fig. 5.7). This illustrates the uncertainties characteristic of the varying attempts to model (parameterize) a complex system involving turbulence, moist thermodynamics and energy fluxes over the full range of time and space scales.

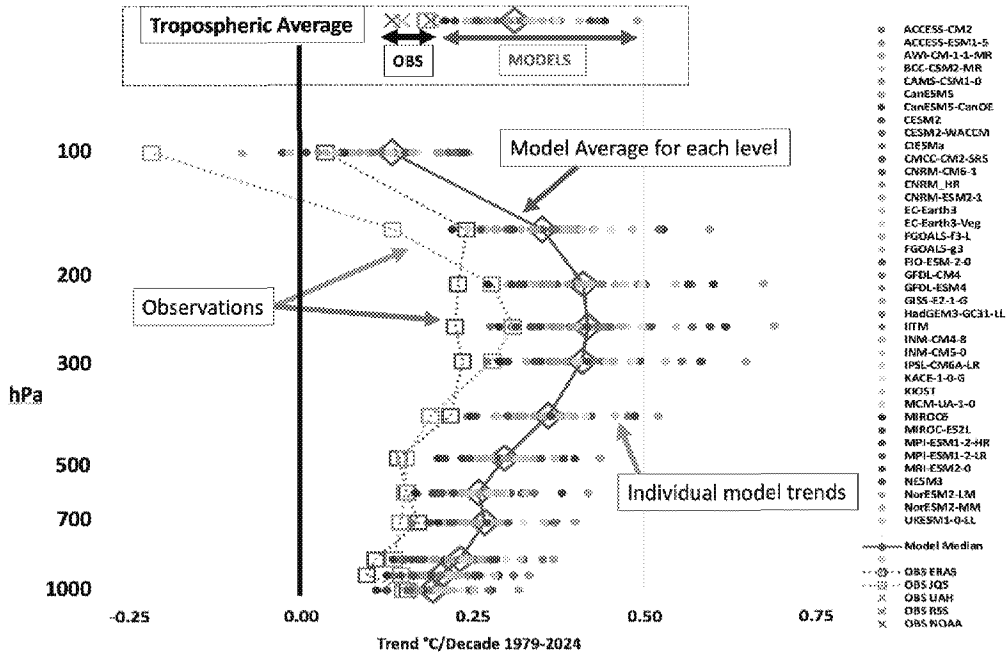


Figure 5.7: Modeled versus observed warming, tropical troposphere. Source: updated from Christy and McNider (2017) including data through 2024. Red line: model average. Green and blue lines: observational series (reanalysis).

This discrepancy has been the source of much controversy, with some arguing that even if there is very little observed warming aloft in the tropics, a “hotspot” still exists in the sense that the warming aloft is greater than at the surface. But there is good evidence that models also exaggerate the amplification rate. Klotzbach et al. (2009), showed that models project greater amplification with altitude than is observed. This result was subsequently confirmed by detailed time series analysis (Vogelsang and Nawaz 2016) who found that the model-observational difference is statistically significant.

This is a case in which models are not merely uncertain but share a common bias compared to observations. This suggests the representation of certain fundamental physical processes in climate model feedbacks have large discrepancies not only among models but against the real climate.

The IPCC AR6 did not assess this issue.

5.5 Stratospheric cooling

An important element of the expected general “fingerprint” of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. The IPCC AR6 acknowledged that cooling had been observed but only up to the year 2000. Thereafter the stratosphere has exhibited some warming, contrary to model projections.

The AR6 WG1 Ch 2 pp. 327-9 states (emphasis added):

“Temperatures averaged through the full lower stratosphere (roughly 10–25 km) have decreased over 1980–2019 in all data products, with **the bulk of the decrease prior to 2000**. The decrease holds even if the influence of the El Chichon (1982) and Pinatubo (1991) volcanic eruptions on the trend, found by Steiner et al. (2020a) to have increased the 1979–2018 cooling trend by 0.06°C per decade, is removed. **Most datasets show no significant or only marginally significant trends over 2000–2019, and the results of Philipona et al. (2018) show weak increases over 2000–2015** in the very lowermost stratosphere sampled by radiosondes....

It is virtually certain that the lower stratosphere has cooled since the mid-20th century. However, most datasets show that **lower stratospheric temperatures have stabilized since the mid-1990s with no significant change over the last 20 years**. It is likely that middle and upper stratospheric temperatures have decreased since 1980, but there is low confidence in the magnitude.

The cited source, Philipona et al. (2018), in an article entitled “Radiosondes Show That After Decades of Cooling, the Lower Stratosphere Is Now Warming”, stated:

“In response to continued greenhouse gas increases and stratospheric ozone depletion, climate **models project continued tropospheric warming and stratospheric cooling** over the coming decades. Global average satellite observations of **lower stratospheric temperatures exhibit no significant trends since the turn of the century**. In contrast, an analysis of vertically resolved radiosonde measurements from 60 stations shows an increase of lower stratospheric temperature since the turn of the century at altitudes between 15 and 30 km and over most continents. Trend estimates are somewhat sensitive to homogeneity assessment choices, but all investigated **radiosonde data sets suggest a change from late twentieth century cooling to early 21st century warming in the lower stratosphere.**”

A combination of tropospheric warming and stratospheric cooling is a commonly-cited “fingerprint” of anthropogenic warming. Stratospheric warming since 2000 coincides with continued surface and tropospheric warming, a pattern that is not found in climate model simulations and is not apparently consistent with the anthropogenic fingerprint.

5.6 Snow cover mismatch

Data compiled by the Rutgers University Snow Lab (undated) show that Northern Hemisphere winter snow cover is not decreasing (Figure 5.8). If anything, it shows an increasing trend.

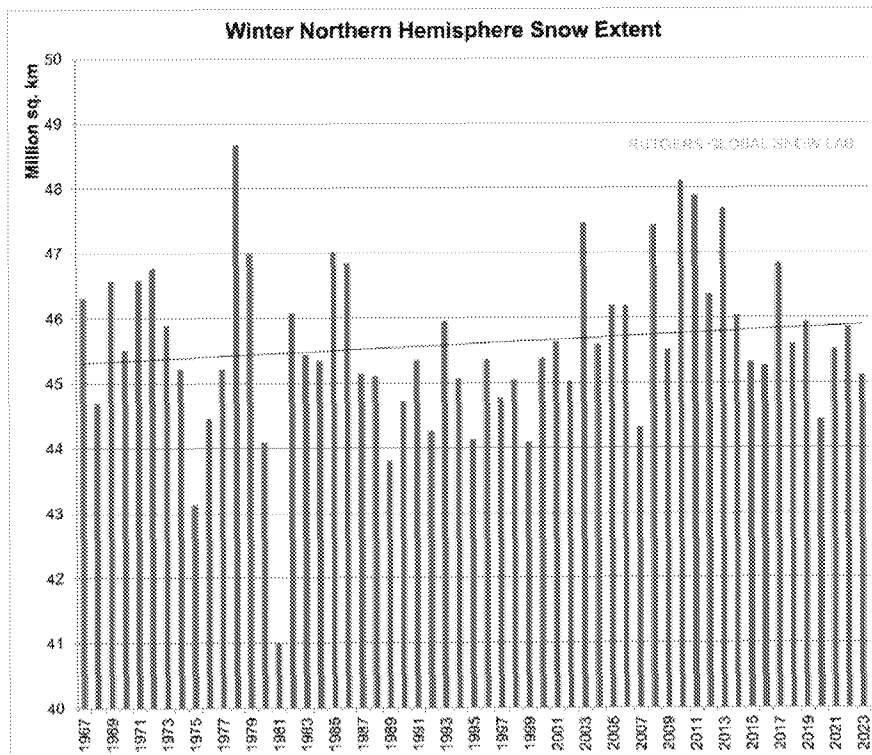


Figure 5.8: Northern Hemisphere Winter Snow extent.

Source: [[HYPERLINK](https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1)

"https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1"] (February 24, 2024)

Yet models project declining Northern Hemisphere snow cover due to climate warming, as described by Connolly et al. (2019).

The climate models were found to poorly explain the observed trends [in Northern Hemisphere snow cover]. While the models suggest snow cover should have steadily decreased for all four seasons, only spring and summer exhibited a long-term decrease, and the pattern of the observed decreases for these seasons was quite different from the modelled predictions. Moreover, the observed trends for autumn and winter suggest a long-term increase, although these trends were not statistically significant.

Connolly et al. (2019).

AR6 largely confines its discussion of changing Northern Hemisphere snow cover extent (SCE) to the Spring season for which models and observations agree on a downward trend. Regarding Winter changes it remarks as follows (AR6 WGI Ch. 2 p. 344):

Assessment of SCE trends in the NH since 1978 indicates that for the October to February period there is substantial uncertainty in trends with the sign dependent on the observational product.

Analysis using the NOAA Climate Data Record shows an increase in October to February SCE (Hernández-Henríquez et al., 2015; Kunkel et al., 2016) while analyses based on satellite borne optical sensors (Hori et al., 2017) or multi-observation products (Mudryk et al., 2020) show a negative trend for all seasons.

AR6 WGI Chapter 9 (p. 1284) points out that the NOAA Climate Data Record showing increased fall and winter SCE is inconsistent with land-based observations and model-based data sets. It notes that using optical satellite imagery to infer SCE in winter is challenging due to cloud cover and decreased solar illumination in winter months.

Focusing on the Pacific Coast states (CA, OR and WA) cold season mountain snowfall that melts in spring and summer provides a substantial portion of warm season water resources. A comprehensive reconstruction of snowfall for the main source regions (Cascades and Sierra Nevada Mountains) indicates no significant trends in annual totals since the late 19th century (Christy 2022).

5.7 Hemispheric symmetry of the planetary albedo

The planetary albedo is the fraction of solar radiation reflected by the Earth back to space, and is an important component of the radiative balance and hence whether the planet will warm or cool over time. An intriguing property of the Earth's albedo is that, on average, the Northern Hemisphere (NH) and Southern Hemisphere (SH) have had very nearly the same albedo at least throughout the fifty-year satellite record (Stephens et al., 2015). This symmetry is surprising, because the SH has much more ocean than land. Since ocean is less reflective than land, the NH should have higher albedo. Clouds (which are highly reflective) are more common in the NH, and so compensate the surface albedo imbalances of the two hemispheres. Datseris and Stephens (2021) show that this cloud compensation comes from the extra-tropical storm tracks of the SH, which are cloudier than those of the NH. While the mechanism for this hemispheric symmetry is unclear, it likely operates on large temporal and spatial scales.

The hemispheric symmetry of the albedo is a simple gross metric for climate models. Rugenstein and Hakuba (2023) defined that metric as the difference between the NH and SH annual mean albedos, expressed as Wm^{-2} of the reflected sunlight, and compiled it for the CMIP6 climate models, as shown in Figure 5.9. Most of the CMIP6 models do not reproduce the small observed asymmetry (about 0.1 Wm^{-2}) and even disagree as to which hemisphere is more reflective. Moreover, the magnitude of the asymmetry ranges up to 5 Wm^{-2} in some models, twice as large as the current anthropogenic forcing (about 2.5 Wm^{-2}).

The significance of unphysical albedo asymmetries in the climate models is not yet fully known. However, other model studies suggest that interhemispheric changes in albedo can alter poleward heat fluxes, meridional temperature gradients, storminess, and differences in hemispheric ocean heat storage. The discrepancy between models and observations further raises issues regarding cloud feedback processes and so more generally diminishes confidence in model projections of the future climate.

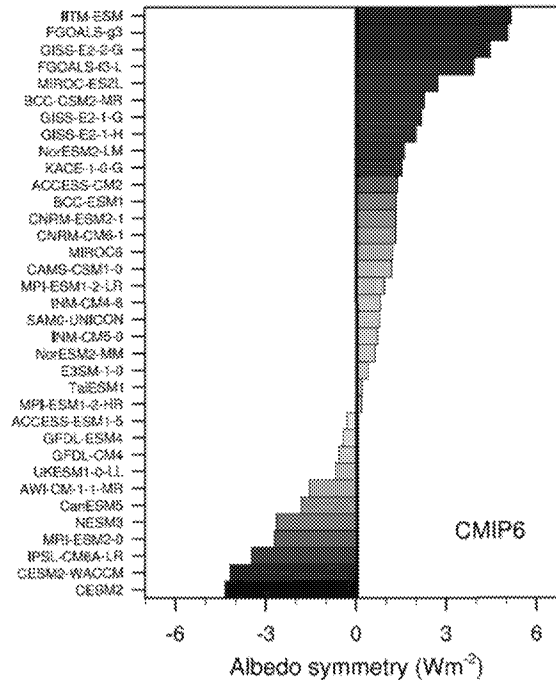


Figure 5.9. Differences in 20-year average reflectivity (albedo) between the Northern and Southern Hemispheres for CMIP6 models used in the most recent IPCC assessment (colored bars). The very small observed difference is indicated by the vertical black line. From Rugenstein and Hakuba (2023).

5.8 US Corn Belt

One of the largest discrepancies between models and observations is in the U.S. Corn Belt, a region of particular importance to global food production. Figure 5.10 shows the warming trends for summertime (June, July, August) for the 12-state Corn Belt (IN, IA, NE, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973-2022. All 36 climate models (red) warm far too rapidly compared to observations (blue).

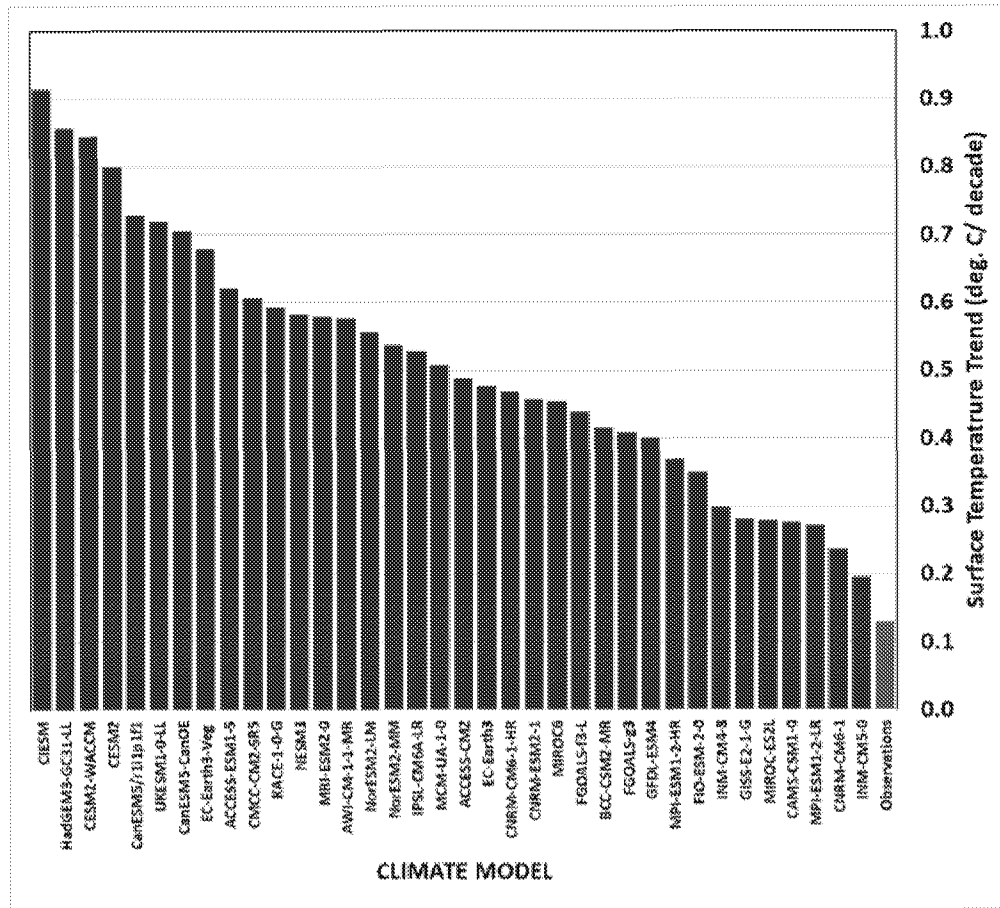


Figure 5.10: Modeled versus observed warming trends in the US corn belt.

As discussed in Chapter 10, the anticipated negative effects of increasing temperatures on U.S. corn yields have not materialized, in contrast to widely publicized studies proclaiming that theoretical future impacts are already being experienced (e.g. Seager et al., 2017).

The IPCC acknowledges limitations in the accuracy of regional climate model outputs. This example shows that users need to assess model projections carefully on a case-by-case basis since local biases may be sufficiently large that the models are simply not fit for purpose. As has recently been noted by two leaders of the modeling community (emphasis added)

... for many key applications that require regional climate model output or for assessing large-scale changes from smallscale processes, we believe that **the current generation of models is not fit for purpose.** (Palmer and Stevens 2019)

To summarize:

- Climate models show warming biases in many aspects of their reproduction of the past few decades.
- They produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft

- They also produce too much stratospheric cooling, too much snow loss, and too much warming in the corn belt.
- The hemispheric albedo difference in individual climate models ranges widely in sign and magnitude compared to observations. The range in Watts/m² is three times larger than the direct anthropogenic forcing of CO₂.
- The IPCC has acknowledged some of these issues but not others.

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6 EXTREME WEATHER

Chapter Summary

Most types of extreme weather exhibit no statistically significant long-term trends over the available historical record. While there has been an increase in hot days in the US since the 1950s, a point emphasized by the IPCC AR6, numbers are still low relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability but long-term increases are not detected. Some increases in extreme precipitation events can be detected in some regions over short intervals but over long periods and at the regional scale the trends do not persist. Wildfires are not more common in the US than they were in the 1980s. Burned area increased from the 1960s to the early 2000's however it is low compared to the estimated natural baseline level. US wildfire activity is strongly affected by forest management practices.

6.1 Introduction

High impact weather extremes, usually related to temperature, precipitation and/or high wind, can disrupt infrastructure and therefore endanger human health and wellbeing. The issue is not whether extremes occur. Rather, it is whether there are long-term (decadal scale) changes in the frequency or character of extremes (“detection”), as well as the extent to which such changes and the attendant changes in hazards are caused by anthropogenic emissions of greenhouse gases (“attribution”; e.g., IPCC AR6 Seneviratne et al. 2021).

It is naïve to assume that any recent extreme event is caused by human influences on the climate. Climate is about the statistical properties of weather over decades, not single events. And, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does not begin to contain all the extreme events that the climate system can create on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes that humans have never observed and thus are absent from the databases used to determine extreme statistics [see *Perils of short data records* below]. For that reason, attributing an extreme event unprecedented in the record requires assumptions about the magnitude of natural variations.

This chapter is concerned with detection of trends in extreme weather, while Chapter 8 considers causal attribution, with Section 8.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed, attribution should not be assumed to follow.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long-Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition, but it can be thought of as the presence of natural variations with strong autocorrelations that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records that are short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme events (Cohn and Lins 2005).

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo shown in Figure 6.1.1. Since human influences on the global climate were negligible before the 20th century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

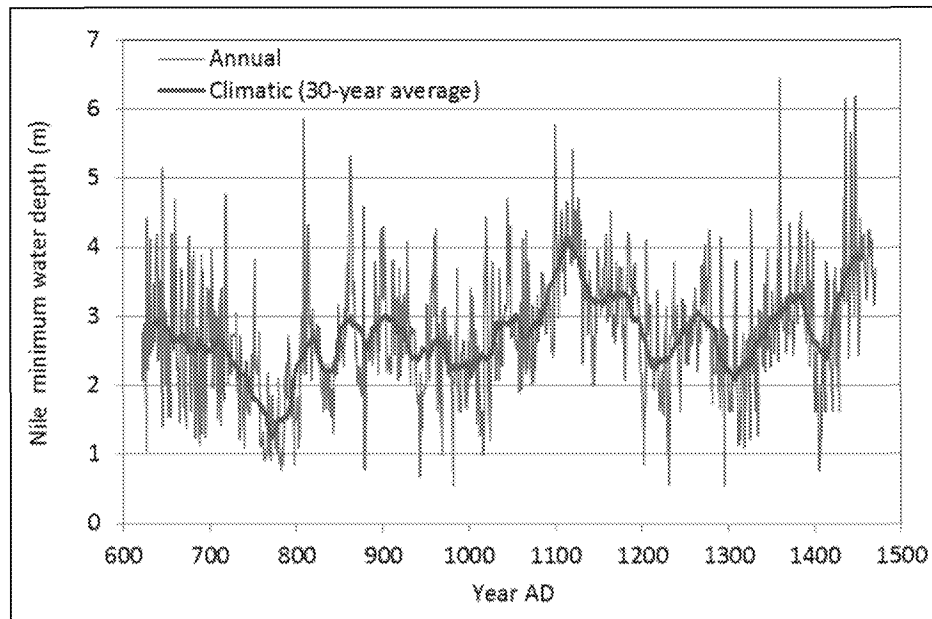


Figure 6.1.1: The annual minimum depth of the Nile River near Cairo over more than 650 years from 622 to 1284 A.D. The data, measured in meters, shows a characteristic pattern of year-to-year fluctuations around longer-term trends. Data from ([HYPERLINK "<https://www.itia.ntua.gr/en/docinfo/1351/>"])

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. An emergent theme is the wide gap between public perceptions and scientific evidence. It has become routine in media coverage, government and private sector discussions, and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and “climate change.” Yet expert assessments typically have not drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

SREX: The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)

AR6: The IPCC Sixth Assessment Report Working Group 1 (2021).

NCA4: The US Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I.

NCA5: The US Climate Science Special Report of the Fifth National Climate Assessment (2023) Volume I.

Note that in the excerpts, *italics* are in the original whereas **boldface** emphasis has been added.

Additionally we present updated data series from standard government sources to provide up-to-date information through 2024 wherever possible.

6.2 Hurricanes and Tropical Cyclones

The AR6 provides the following assessment of tropical cyclones (TCs; used here as a synonym for hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades . . . There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2023)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows **no trend in the frequency of U.S. landfall events**. (IPCC, 2021)

Since 1980, when satellite observations fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 6.2.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (Maue, 2025). There is substantial year-to-year and decadal variability a weak decreasing trend in the number of hurricanes and a slight but insignificant increasing trend in the number of major hurricanes These two trends combine to create an increasing trend in proportion of major hurricanes.

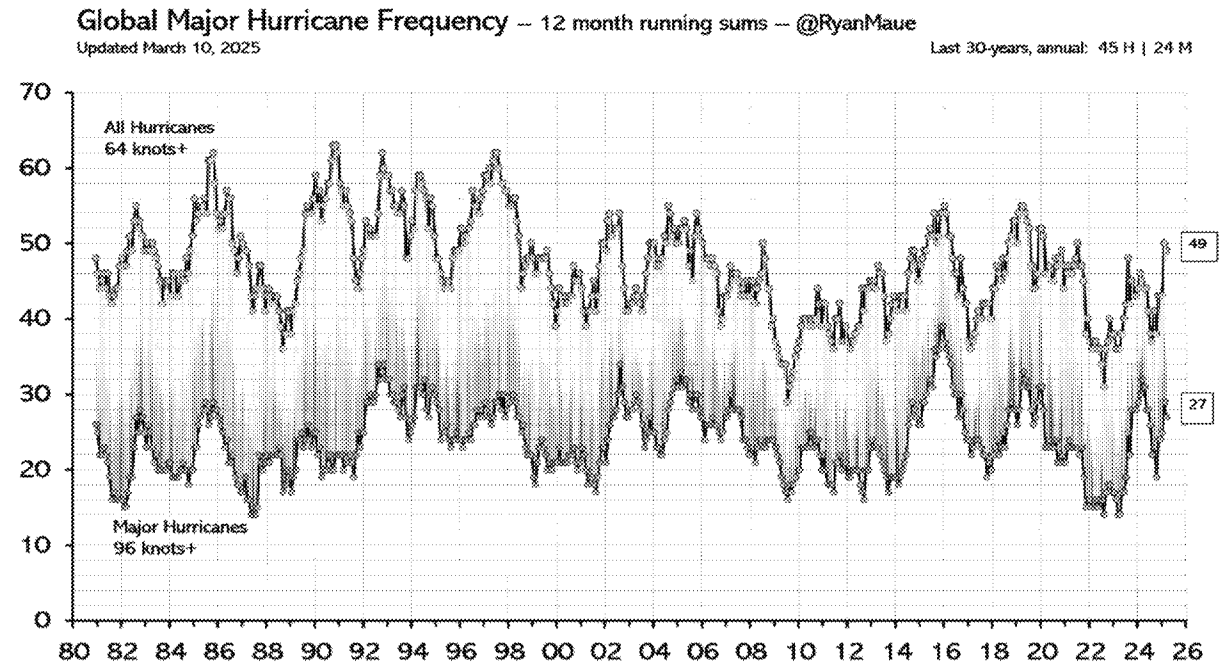


Figure 6.2.1: Global frequency of hurricanes and major hurricanes since 1980.

Global hurricane statistics are dominated by the Northwest Pacific Ocean, which accounts for ~35 percent of total global hurricanes, whereas the Atlantic accounts for ~15 percent of global hurricanes (CSU, 2025). Data in the Atlantic basin extends further back than in the other ocean basins, and is most relevant to U.S. policy makers.

Figure 6.2.2 shows the frequency of Atlantic hurricanes and major hurricanes (Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (Vecchi and Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 was a period of exceptionally low activity, with high values of hurricane activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and even in the 1930's.

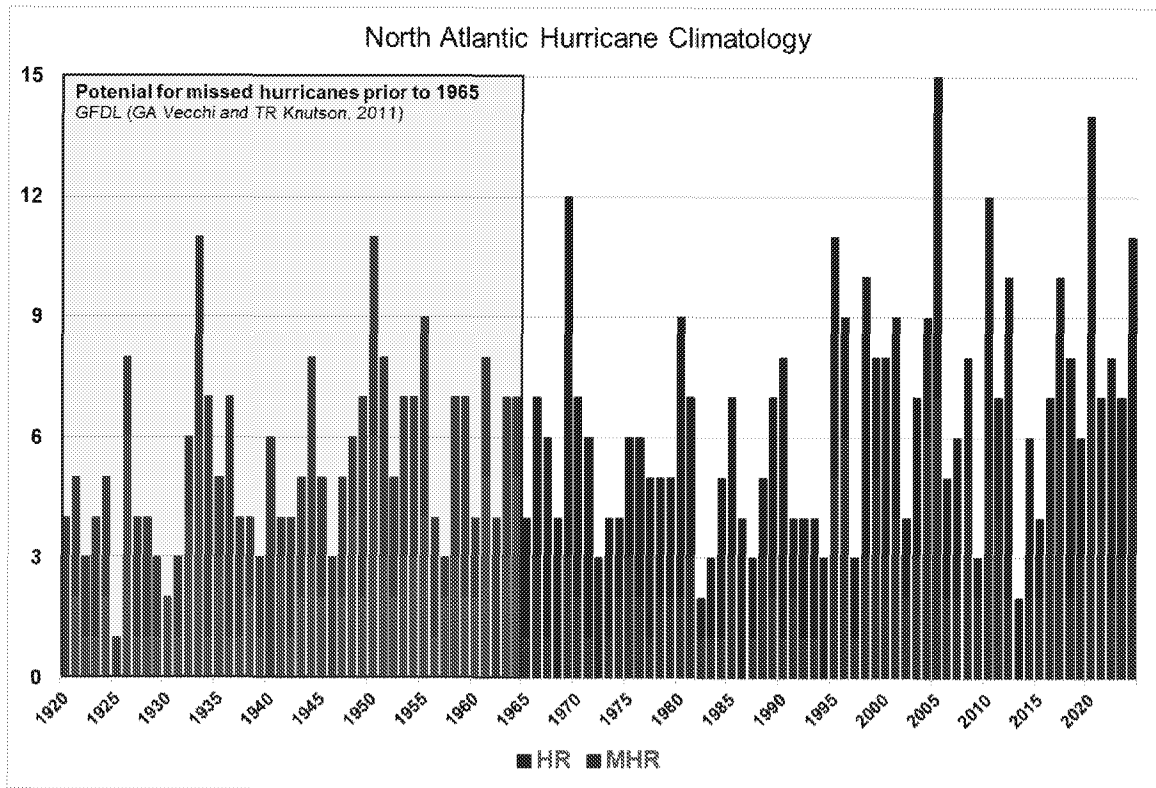


Figure 6.2.2: Atlantic frequency of hurricanes (HR) and major hurricanes (MHR) since 1920. Source (NHC, 2024)

Figure 6.2.2 shows that Atlantic hurricanes vary strongly on decadal and multidecadal time scales. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is manifest in basin-wide sea surface temperature and sea level pressure fluctuations connected to large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present, but in its cool phase during 1971-1994. The AMO has its greatest impact on the number of major hurricanes (Category 3+), identified by Goldenberg et al. (2001) to be associated with above normal SSTs and decreased vertical shear in the AMO warm phase (see also Bell and Chelliah, 2006; Klotzbach et al., 2018).

Klotzbach et al. (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 6.3.3 updates their analysis through 2024. While the largest numbers of hurricanes are from 2004, 2005 and 2020, there is no statistically significant trend since 1920. Figure 6.2.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, there were no major hurricanes striking the U.S from 2006 through 2016, the longest such period since 1920.

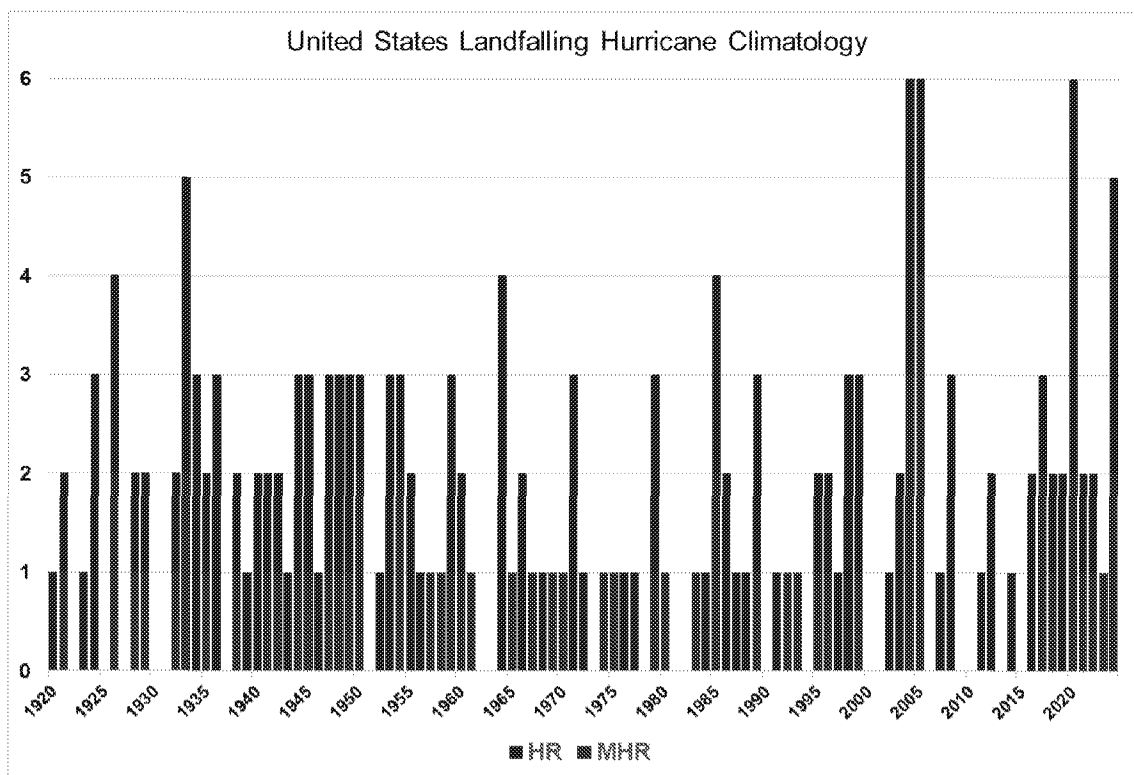


Figure 6.2.3: US landfalling frequency of hurricanes (HR) and major hurricanes (MHR) since 1920.
Source (NOAA HRD(a), 2024)

Substantial interannual to multidecadal variability in U.S. landfall activity is seen Figure 6.2.3. Klotzbach et al. (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini et al. (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19th century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record, is 1886, with 7 landfalls,

Table 6.2.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the 21st century.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. While it has long been hypothesized that a rising global sea surface temperature would cause an increase in hurricane intensity, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

Table 6.2.1 Strongest hurricanes to make landfall along the US coast. Source (NOAA HRD(b), 2024)

Rank	Year	Landfall	Name
		Wind (MPH)	
1	1935	185	"Labor Day"
2	1969	175	Camille
3	1992	165	Andrew
4	2018	160	Michael
5	1856	150	"Last Island"
5	1886	150	"Indianola"
5	1919	150	-----
5	1932	150	"Freeport"
5	2004	150	Charley
5	2020	150	Laura
5	2021	150	Ida
5	2022	150	Ian

6.3 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. However, the NCA4 noted that heatwave activity in the US reached a peak in the 1930s.

AR6: “It is *virtually certain* that hot extremes (including heatwaves) have become **more frequent** and **more intense** across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe” (SPM, A3.1)

AR6: “In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA.” (Chapter 11, p 1550)

NCA4: “Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year **increased** in some parts of the West over the past century, but there were **decreases** in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net **decrease**, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]).” (pp. 190-191)

NCA4: “Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, **heat wave magnitude reached a maximum in the 1930s.**” (pp. 190-191)

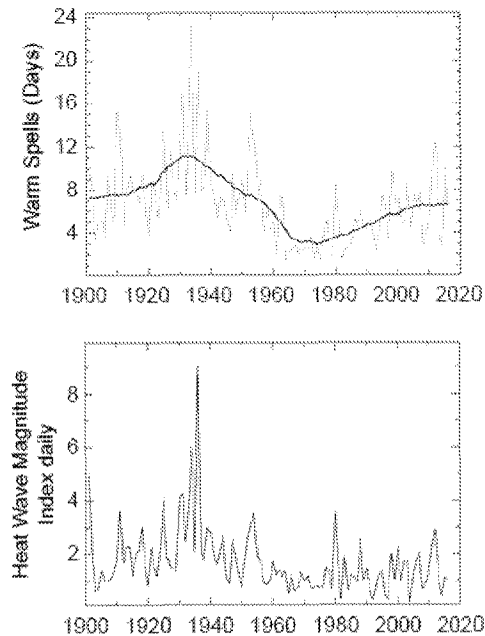


Figure 6.3.1: US Heat waves since 1900. Source: NCA4 Figure 6.4

6.3.1 Temperatures in the US are becoming less extreme

Daily maximum temperatures in the warm season (Tmax, May-Sep) and daily minimum temperatures in the cold season (Tmin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 6.4.2; Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.

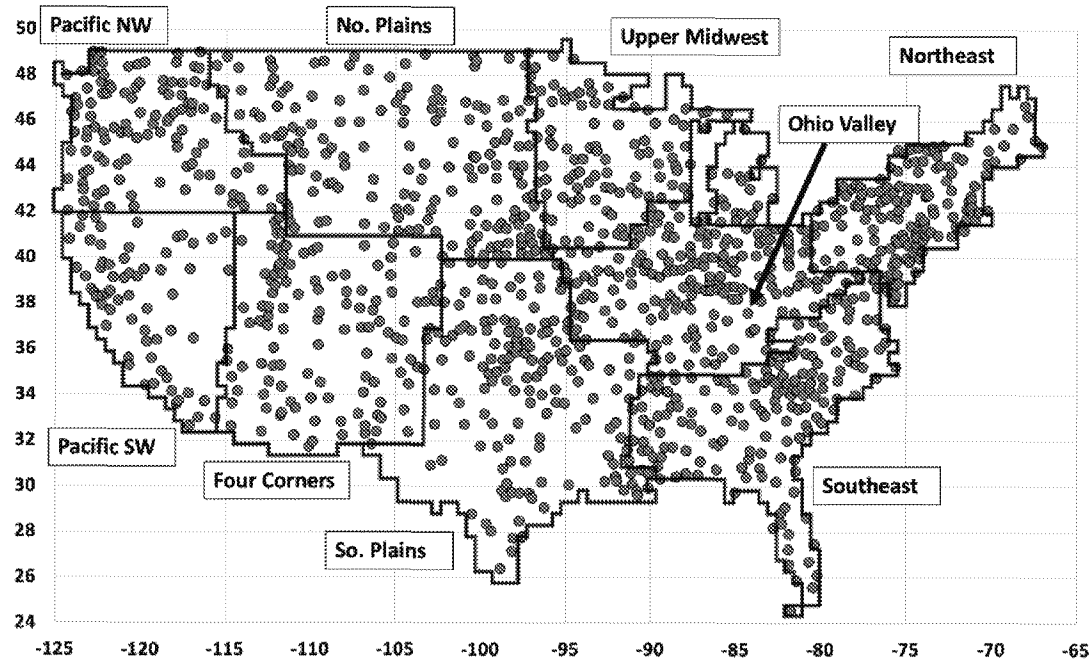


Figure 6.3.2 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for Tmax would be 1.21 ($=153/126$) per station per year and for Tmin 0.96 ($=122/126$) per station per year.

Figure 6.3.3 shows the observed distribution in time of the occurrence of these extreme events. There is a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the Tmax records and 59% of the Tmin records occurred in the first half of the period (1899-1961).

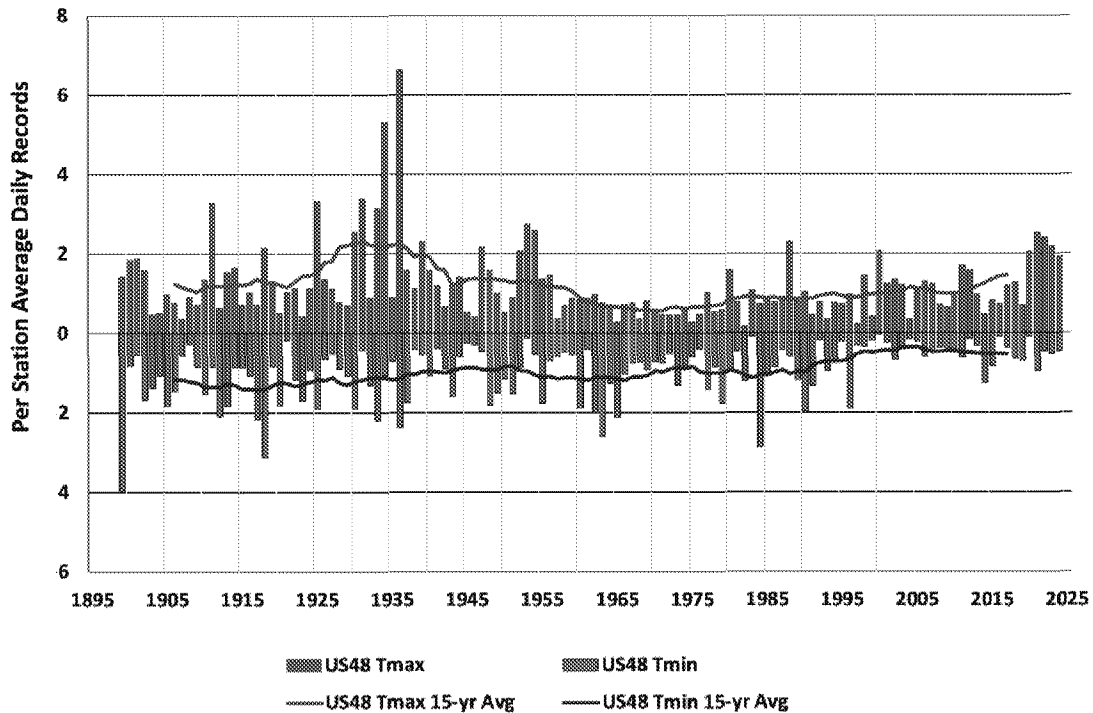


Figure 6.3.3 Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898. US48: contiguous US states. Tmax: maximum temperature. Tmin: minimum temperature.

On the cold side, the Valentine’s Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 in 2nd place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme Tmax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR6, NCA4). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 6.3.4. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 6.3.4 shows the 15-year trailing average of this measure, which has clearly declined over the past century.

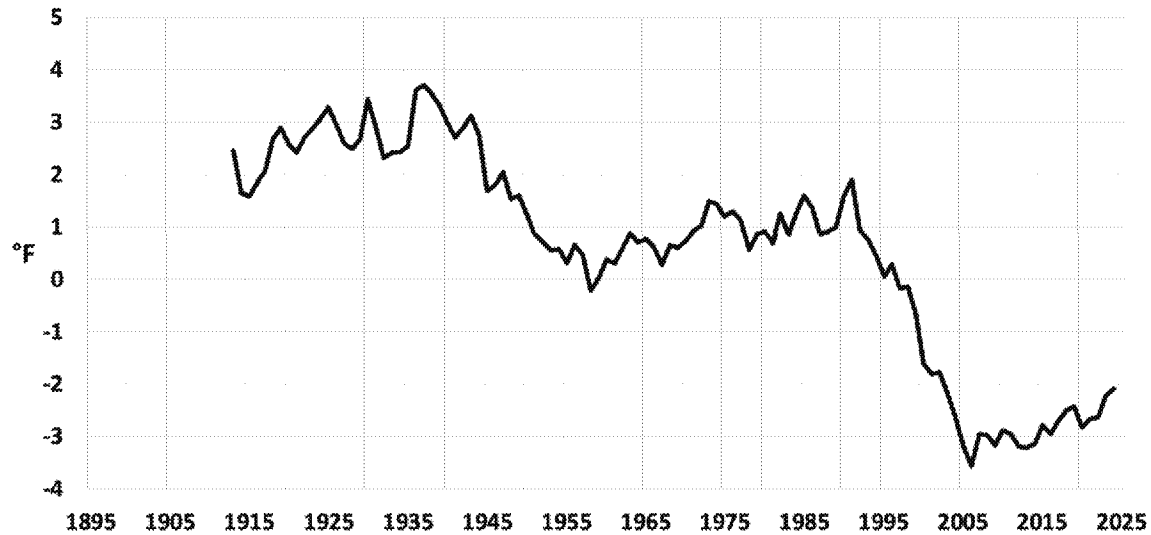


Figure 6.4.4. 15-year trailing average of the difference each year of each station’s hottest warm-season Tmax and coldest cold-season Tmin relative to the long-term average. Source: USHCN, author calculations.

The average difference for each station between the hottest summer Tmax and coldest winter Tmin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter Tmin, but a decline in summer Tmax is also a factor. The rise in Tmin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Spencer et al. 2025).

In summary, while temperature extremes are regularly experienced in the U.S. and attract a great deal of media attention, long term records show the US climate has become less extreme over time (milder) when measured by the range between warm season maxima and cold season minima.

6.3.2 Exceedances of a heat threshold

Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

“The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021.”

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F Tmax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F Tmax temperatures, a small change will not have much impact on the results. In the past 126 years, the average CONUS station

experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, such threshold analyses must be interpreted with caution.

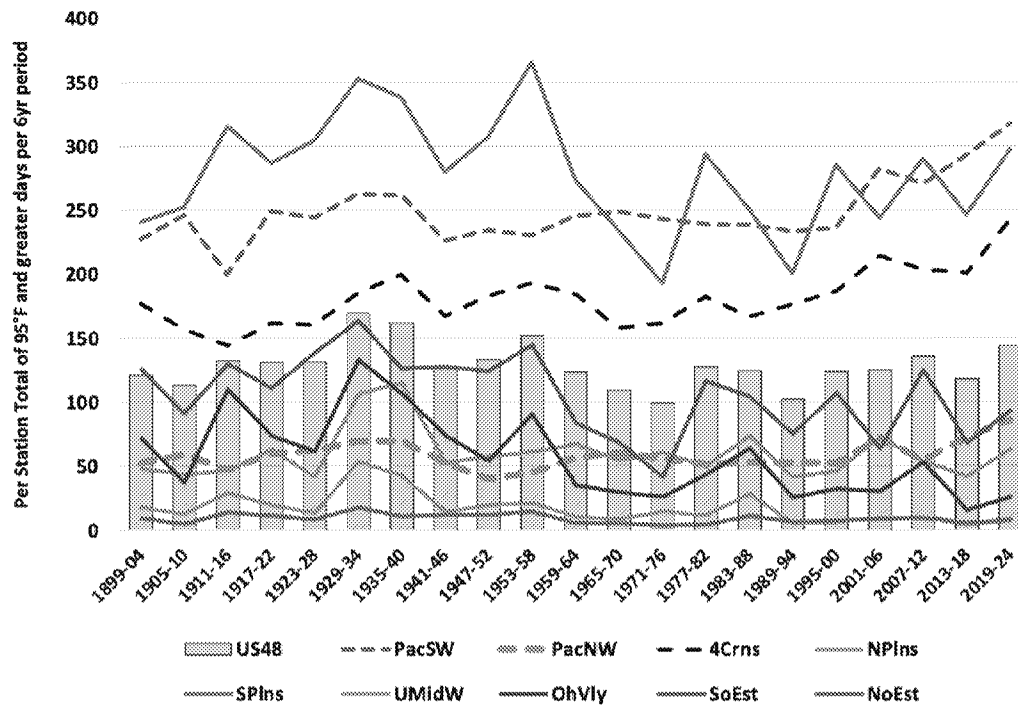


Figure 6.3.5. Total number of days $\geq 95^{\circ}\text{F}$ in 6-yr periods, US 48 (bars) and regions (lines). Interval is 6-years as this is divisible into 126. Source: USHCN, author calculations. US48: contiguous US states. See Figure 6.3.2 for region names.

Figure 6.3.5 shows that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not, and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 referenced in the NCA5 quote will be examined more closely in Section 8.5. The evidence indicates that it was a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was +10.8 C, the most extreme Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero (+0.03 C, Mass et al. 2024).

The NCA5 heading “The Risk of Temperature Extremes is Changing” suggests pervasive positive trends are now being observed in threshold temperatures, but that is not evident in the figures above.

6.3.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90th percentile for that day and that lie within a period of at least six consecutive days. This is equivalent to the method used in NCA4, except that the reference period here is the entire record 1899-2024 while NCA4 truncated the reference period to 1961-1990, which was a cool period. That truncation boosts positive results (days exceeding the 90th percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).

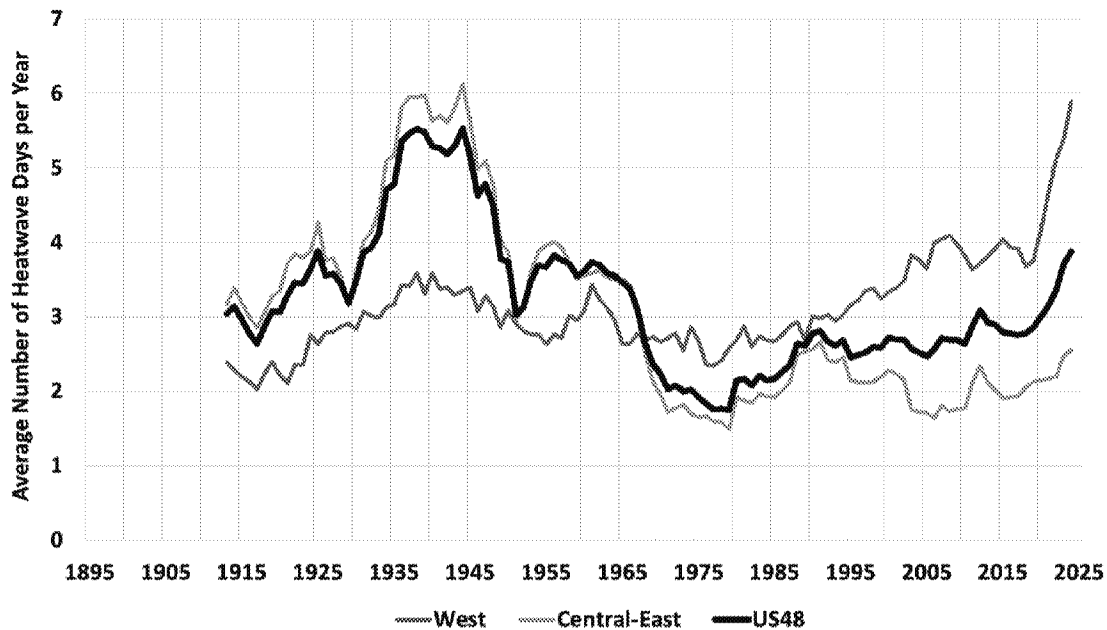


Figure 6.3.6 15-year trailing average of number of heatwave days per year per station in the CONUS (black line) and four regions: West (red), Central-east (green).

Figure 6.3.6 indicates that there are regional variations in heatwave activity. The excessive heat of the first half of the 20th century occurred primarily in the eastern two-thirds of the nation, while the West has seen a recent increase of heatwave days (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago, consistent with the upper panel of our Figure 6.4.1 taken from NCA4.

This metric varies significantly with region. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

The analysis of heatwaves is an example of why it is important to consider complete datasets and appropriate metrics. The NCA5 directs readers to the website [[HYPERLINK](#)

"<https://www.globalchange.gov/indicators/heat-waves>"] (USGCRP 2023) to view a figure showing the number of urban heatwaves by decade from the 1960s, which we reproduce as Figure 6.3.7.

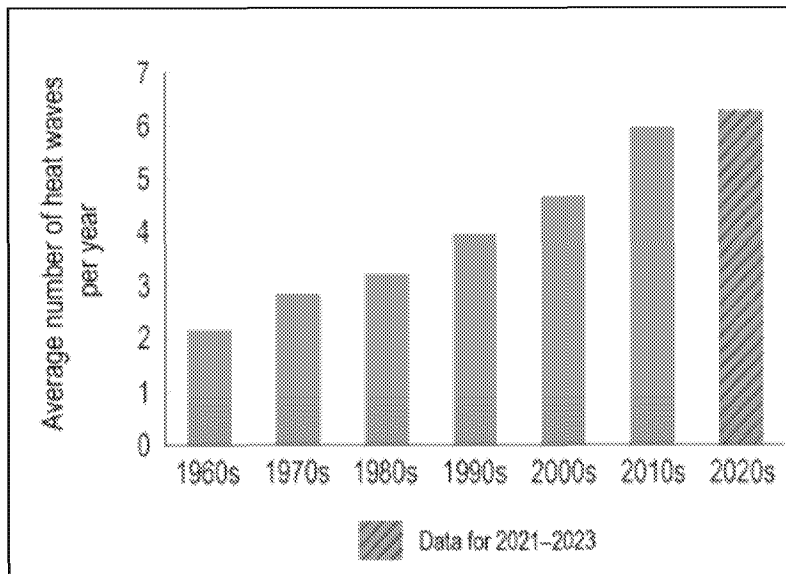


Figure 6.3.7: Average number of urban heatwaves per year for 50 large U.S. metropolitan areas. From [HYPERLINK "<https://www.globalchange.gov/indicators/heat-waves>"]

The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave used is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the *minimum* apparent temperature (combination of temperature and humidity) exceeds the 85th percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

Given the unusual heatwave definition and urban focus, these increasing values since 1960 presented in USGCRP (2023) are not informative about long term trends or the influence of GHG emissions for at least two reasons. First, as shown in Figures 6.3.1 and 6.3.6, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. Second, post-1960 urbanization in these cities is a major factor in the rise of T_{min} relative to co-located T_{max} and relative to T_{min} at nearby rural stations. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer T_{max} (especially in rural areas) is a better metric for detecting changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

6.4 Extreme precipitation

The IPCC AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: “The frequency and intensity of **heavy precipitation events have increased** since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence).” (SPM A3.2)

AR6: “In North America, there is robust evidence that the **magnitude and intensity of extreme precipitation has *very likely* increased** since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018 “(Chapter 11, p. 1560)

The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme precipitation events are in the Northeast and the smallest in the West, a pattern counter to the changes in temperature extremes.

McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast using a trend model with a non-parametric variance estimator robust to the complex autocorrelation properties of precipitation data. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region.

These findings have been updated for this report with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), also adding 27 stations in the Northeast (1888ff from Buffalo NY to Eastport ME). The locations are shown in Figure 6.4.2. The stations were selected on the basis of availability of long-term high-quality records. The regions are each associated with important features of extreme precipitation behavior. The Pacific coast is associated with landfalling atmospheric rivers. The NCA report has indicated that the Northeast has experienced the greatest increase in extreme events. The Southeast is also a place noted in the NCAs for increased extreme events.



Figure 6.4.2: Locations of precipitation monitoring stations used in this report. Orange: Pacific coast. Blue: Northeast. Green: Southeast.

The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then followed by further explanation.

Pacific Coast heavy rainfall events

- Average precipitation trend is statistically significant (downwards) in Astoria OR; insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst series of such events in recent history was the so-called ARkStorm that occurred between December 1861 and January 1862; it dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

BOX: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 7.2.

Event	Record (inches)	Year
3-day	6.94	2023
5-day	8.55	2023
14-day	12.62	2023
30-day	18.93	1998

Table 6.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent years. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences. [Note: “2023” indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 6.3 shows that the record-setting events all happened in the 1860s. Furthermore 2023 is now not even in 2nd place but falls to 3rd or 4th place. Also, comparing the records of the

two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Event	Record (inches)	Year	Rank of 130-yr extreme
3-day	8.85	1867	3
5-day	9.80	1867	3
14-day	19.05	1862	4
30-day	28.25	1862	2

Table 6.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ArkStorm that struck the region. Evidently such extreme events, “unprecedented” in our 1895-2024 sample, have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

We examine occurrences of 5-day deluges as follows. Taking the Pacific coast as an example, a 130-year span contains 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values across the sample. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation, then the total number of these events across all stations should be evenly spread out over the years. In Fig. 6.5.3 we show the distribution in time of these events for the Pacific coast. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of such precipitation metrics, there is no indication of a tendency to become more frequent over time.

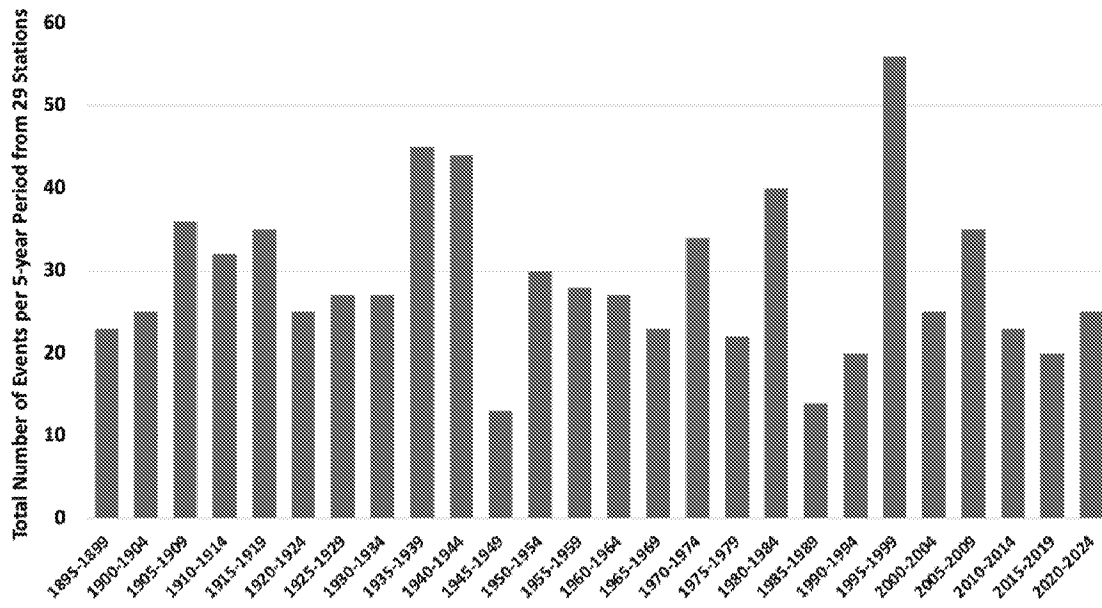


Figure 6.5.3. The time distribution by 5-year periods of the 26 heaviest (1-in-5 yr) occurrences for 29 stations on the Pacific coast.

Southeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in Mobile AL and Quitman GA, and insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile AL, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA, and insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

Figure 6.5.4 shows the same calculation for the last 150 years in the Southeast humid zone. The temporal pattern of 5-day totals of the 1-in-5yr heavy events is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 -- an increasing frequency of heavy events due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

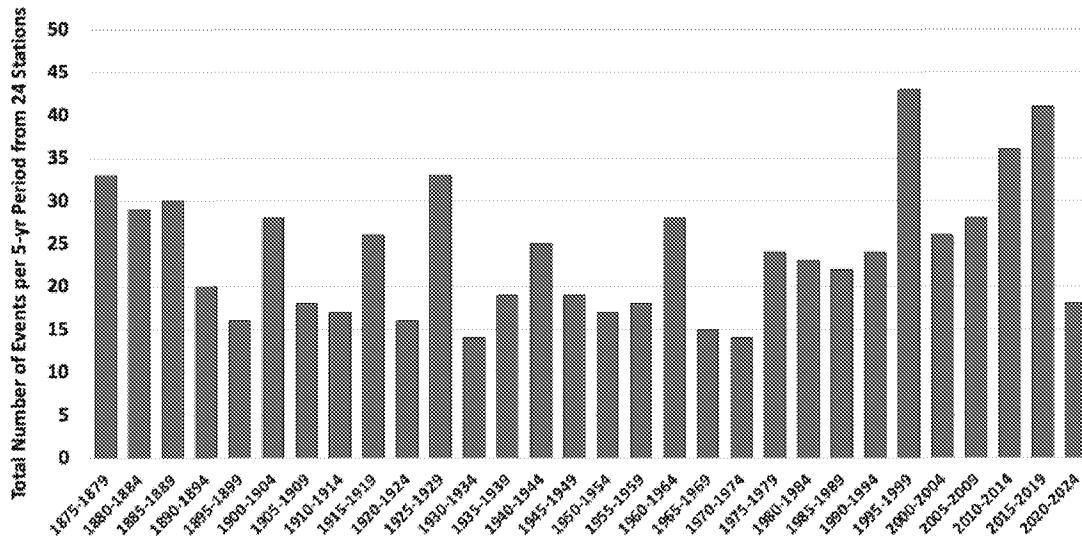


Figure 6.5.4. As in Fig. 6.5.3 but for the heaviest 30 (1-in-5yr) events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

Northeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in 12 of 27 locations and also in the regional average.
- The trend in rainfall variance is positive and significant in Portland ME, Albany NY, Buffalo NY and Eastport ME, but insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland ME, Gardiner ME and Eastport ME, but insignificant elsewhere.
- When averaged over all stations in the region, there is no statistically significant trend in either the precipitation variance or maximum

Fig. 6.5.5 shows the same calculation for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest temporal variations in time. In this region, 72% of events occur during June to October and are dominated by incursions of hurricanes, tropical storms, or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it merits a closer examination.

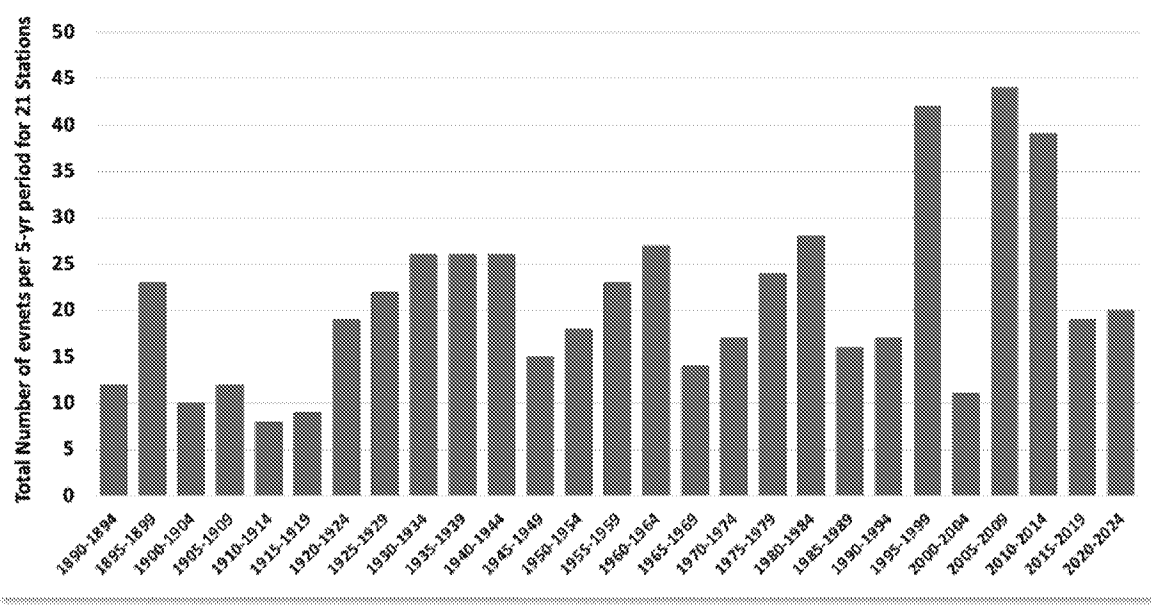


Figure 6.5.5. As in Fig. 6.5.3 but for the heaviest 27 (1-in-5yr) 3-day precipitation events for 27 Northeast stations from NY to ME, including Montreal.

There is a noticeable clustering of extreme events from 1995 to 2014. Howarth et al. (2019) examined a similar region as in Fig. 6.5.5 that includes PA and NJ and reported significant differences between two 18-year periods, 1979-96 and 1997-2014, of various precipitation extremes, including a 317% increase in 24-hr events exceeding 6 inches, while we find a 51% increase over the same years. However, Figure 6.5.5 shows that frequency drops sharply after 2014, returning to the long-term average in the subsequent 5 year intervals, again illustrating the perils of drawing conclusions from short-term trends in highly variable metrics.

Also the high percentage increase in the Howarth et al. sample is associated with small numbers at relatively few locations: there were only 6 in the first period and 25 in the second across 58 stations. Most of the stations did not record such an event. If there is a region-wide increase in heavy events, it should be seen in the average across all stations. Figure 6.5.6 shows the average precipitation in the 1-in-5 yr events across the NE. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 6.5.5 and 6.5.6 thus suggest that though there was a surge in the number of events at a few locations during the 1995 to 2014 interval, there was no regional pattern and the change did not persist beyond 2014.

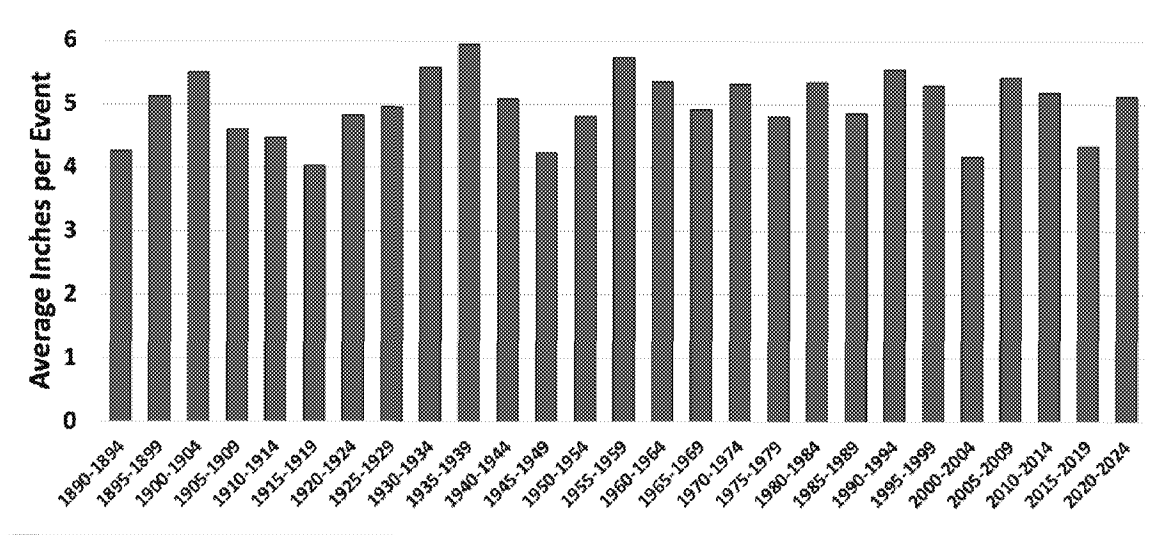


Figure 6.5.6. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, “The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s.” The question then becomes: was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 6.5.6 where the amount-per-event has remained steady over the 135-year period.

There is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, “Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 6.5.5.

In summary, some regions show short-interval increases in extreme precipitation events, consistent with natural variability. But analysis of long term, nationwide historical records taking into account the autocorrelation properties of precipitation data does not support the claim that extreme short-duration rainfall events are becoming more frequent or intense.

6.5 Tornadoes

AR6 assesses tornado trends in the US as follows:

[O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

The monitoring of weak tornadoes has changed over time. The growth of rural populations and the increasing ability to take video with hand-held devices has led to more frequent reports of weak tornadoes that produce minimal damage. In contrast, strong to violent tornadoes have been observed more consistently over time. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes as shown in Fig. 6.6.1a. Note that tornado strength is measured by the damage it produces, not by the visual appearance of the funnel. Limited real-time observational capabilities in earlier decades did not prevent identification because strong to violent tornadoes leave much more damage which will be assessed later even if the tornado itself was not observed.

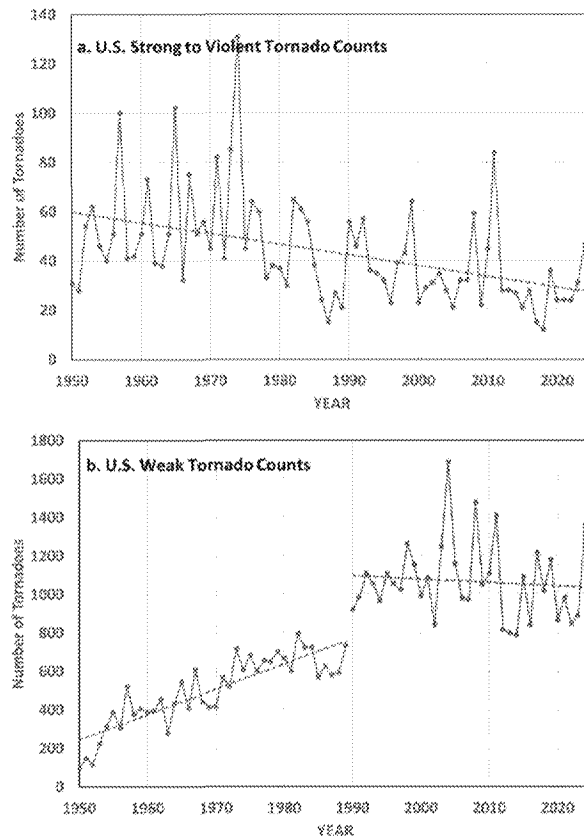


Figure 6.6.1. Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms Prediction Center data, available at https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv

To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

6.6 Flooding

Changes in floods were assessed as follows:

AR6: “The SREX **assessed *low confidence* for observed changes in the magnitude or frequency of floods** at the global scale. This assessment was confirmed by the AR5 report. The SR15 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.” (Chapter 11.5)

AR6: “[T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is ***low***.” (Chapter 11.5)

NCA4: “Trends in extreme high values of streamflow are **mixed** across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude **but does not provide robust evidence** that these trends are attributable to human influences” (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in Section 6.5 of absence of coherent changes in extreme precipitation.

6.7 Droughts

Assessments of drought trends were as follows.

AR6: “**Few** AR6 regions show observed increases in meteorological drought” (Section 11.9, p. 1575),

AR6: “**Increasing trends in agricultural and ecological droughts have been observed on all continents** (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions.” (Chapter 11 Summary)

NCA4: “As a consequence of this increased precipitation, **drought statistics over the entire CONUS have declined.**” (p. 233)

NCA4: “Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the **1930s remains the benchmark** drought and extreme heat event in the historical record (very high confidence).” (p.231)

SREX: “From a paleoclimate perspective, **recent droughts are not unprecedented**, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia.” (p. 170)

As shown in Figure 6.8.1, US long term data shows an insignificantly declining trend toward extreme dryness (-0.00001% per year)

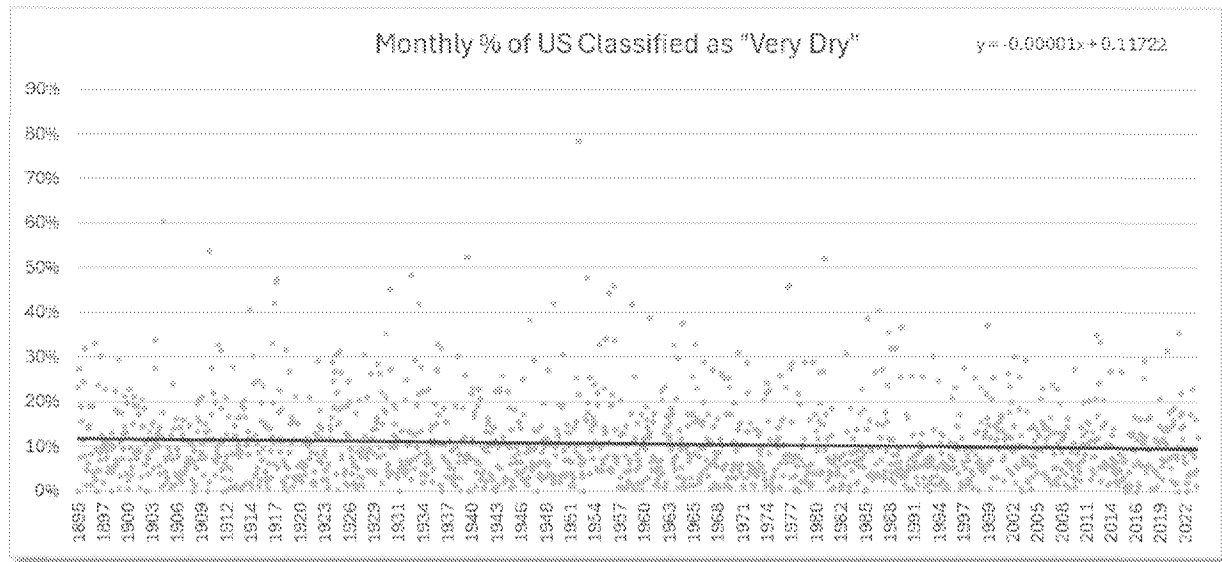


Figure 6.8.1: US dryness (%) 1895—2023. Source: NOAA [[HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0" \]](https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0)]

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

In summary there is no evidence of increasing drought frequency or intensity in the U.S. or globally over recent decades.

6.8 Wildfires

The IPCC has not provided an assessment of wildfires. As shown in Figure 6.9.1, global wildfire activity as measured by European Space Agency shows a downward trend in the 21st century.

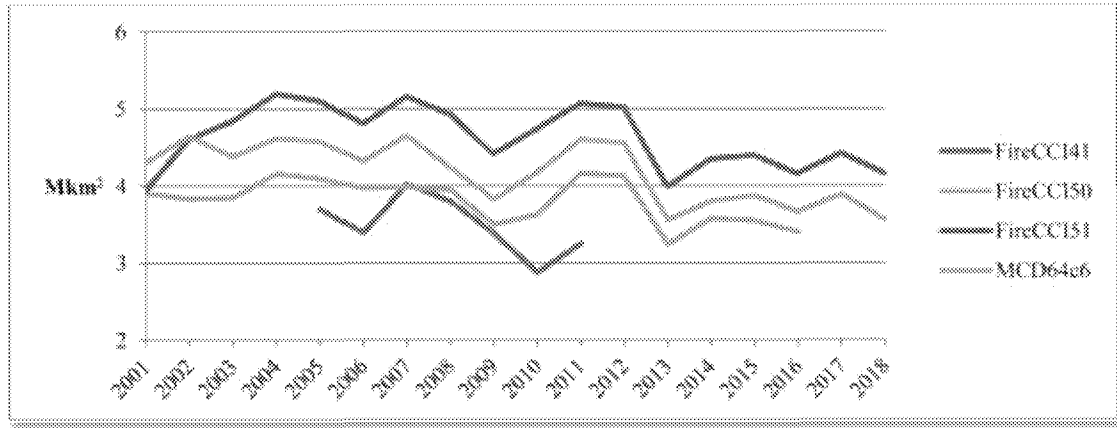


Figure 6.9.1: Global wildfire area 2001-2018. Source: From Lizundia-Loiola et al. (2021). The different coloured lines represent data products derived from different satellites and algorithms

Global data show that wildfire coverage is constant or declining on every continent (Samborska and Ritchie, 2024).

Active fire suppression since 1900 makes it difficult to establish a natural baseline for wildfire activity in the U.S. Paleoclimatic evidence indicates that past activity was much higher than today. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years and also fit a model to predict fire activity as a function of climatic conditions. Their results are summarized in Figure 6.9.3 below (from Figure 2 in their paper). There has been a growing wildfire deficit over the 20th century. In other words, however much fire was observed in the 20th century, it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.

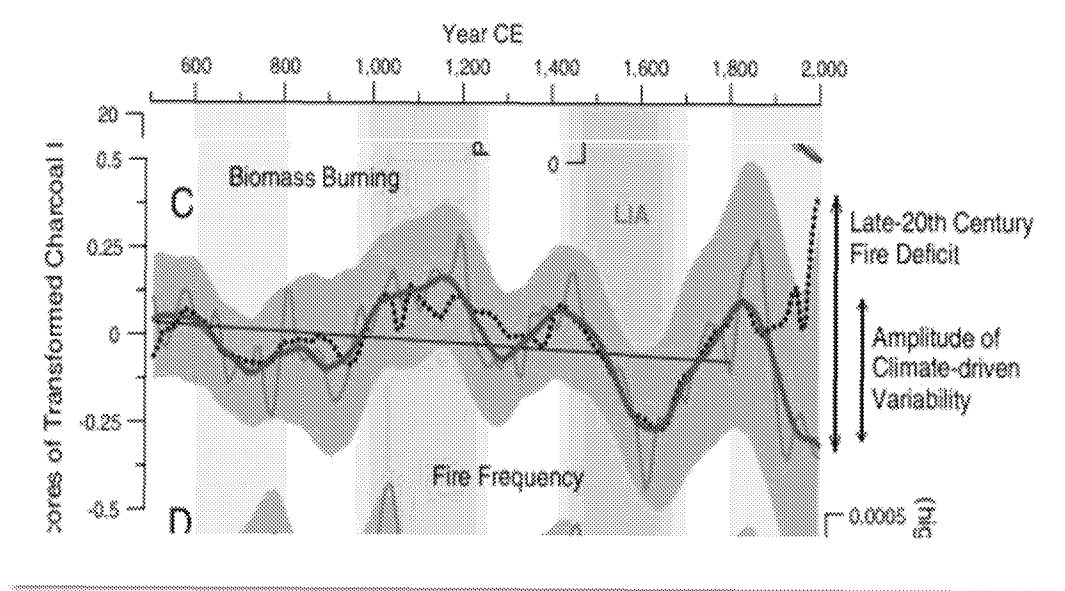


Figure 6.9.2 Fire frequency and fire deficit in the US. The red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based climatic conditions. model. Source: Copied from Marlon et al. (2012)

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 6.9.2.

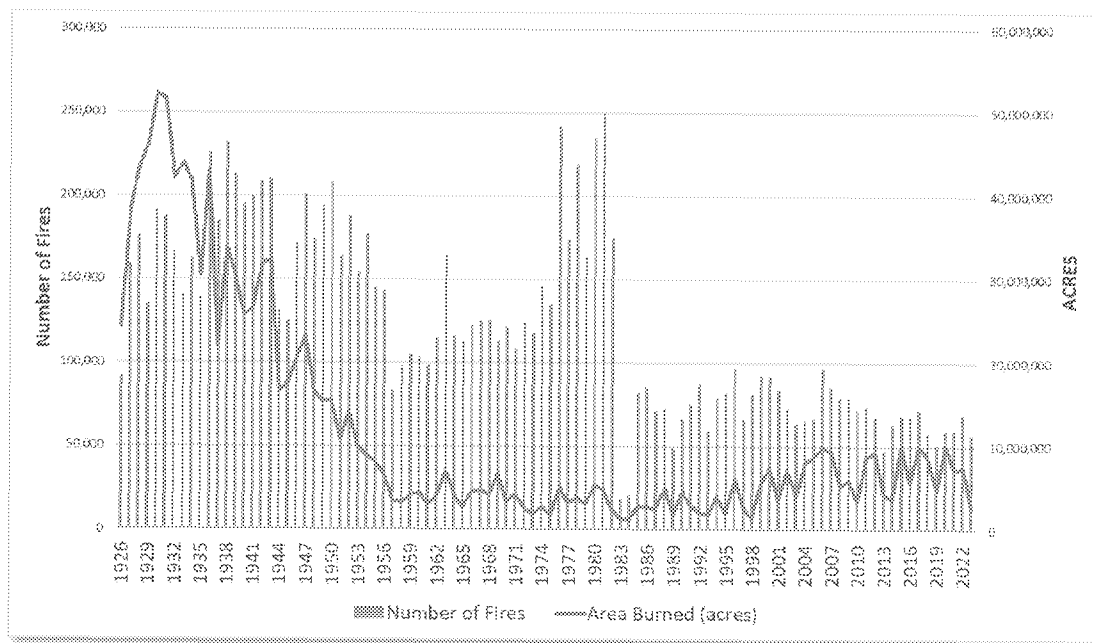


Figure 6.9.2: US wildfires 1926 to 2023. Source: Post-2018: National InterAgency Fire Center data

Pre-2017 webarchive.org.

The NIFC has removed the pre-1960 data from its current website on the grounds that measurement methods changed after 1960 making the comparison unreliable. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life including humans. Science has confirmed the overall benefit and necessity of the occurrence of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile forest fire remains the 1910 Big Blowup fire which destroyed over three million acres including the elimination of entire towns like Taft, MT (Apple, 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal to defeat all forest fires (Forest History Society, 2022). This led to the 10 am rule in 1935 requiring that all fires spotted on any day had to be controlled by 10 am the following day (National Forest Foundation, 2022).

While defeating all fires seemed a noble goal, questions began to arise as to whether this behavior “followed the science” (US Forest Service, 2022). Over time the U.S. Forest Service has begun to rethink its goals, recognizing that new approaches such as prescribed burns, fuel elimination, and controlled wildfires are more appropriate (Sommer, 2016). Recent research is validating this approach and recognizing that more frequent smaller fires likely result in the healthier forests, water ecosystems and biodiversity (Stephens et al., 2021).

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7 CHANGES IN SEA LEVEL

Chapter Summary

Since 1900, global average sea level has risen by about 8 inches. Sea level change along U.S. coasts is highly variable, associated with local variations in processes that contribute to sinking and also ocean circulation patterns. The highest levels of sea level rise along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions - each of these locations is associated with substantial local land sinking (subsidence) unrelated to climate change.

Extreme projections of global sea level rise are associated with an implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothesized ice sheet instabilities. In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the sea level rise has already occurred by 2025 and at a lower rate than predicted. US tide gauge measurements shown herein reveal no obvious acceleration beyond the historical average rate of sea level rise.

7.1 Global sea level rise

Global sea level rise is arguably the most important climate impact driver that is unambiguously associated with increasing temperatures. At the global level, warming raises sea level through thermal expansion of the volume of sea water and through melting of glaciers and ice sheets. Variations in land water storage are another important factor. At the regional scale, sea level change is influenced by large-scale ocean circulation patterns, and geologic processes and deformation from the redistribution of ice and water. Locally, vertical land motion from geologic processes, ground water withdrawal, and fossil fuel extraction are also important.

The IPCC AR6 estimates that global mean sea level increased by 7.9 (5.9–9.8) inches between 1901 and 2018, with the rate of sea level rise accelerating in recent decades. At the ocean basin scale, sea levels have risen fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018 (B. Fox-Kemper et al., 2021). The rate of global sea level rise is estimated to be 0.12 inches/year (for reference, 0.12 in is the height of two stacked pennies) (NASA, 2020).

The observing systems for global sea level rise have advanced significantly in the satellite era, particularly with the advent of satellite altimeters since 1993. Local tide gauges have provided useful data for the past century, and even longer for a few locations. Following the end of the Little Ice Age in the mid-nineteenth century, tide gauges show that the global mean sea level began rising during the period 1820–1860, well before most anthropogenic greenhouse gas emissions.

7.2 U.S. sea level rise

Observed and predicted rates of mean global sea level rise might have little scientific relevance for specific locations, owing to local processes (NOAA, 2025). Figure 7.1 shows that in Canada and Alaska (and also northern Washington), sea level is actually decreasing, owing to uplift from glacial rebound. Most of the Pacific coast tide gauges show rises between 0.12 inches/year, while largest U.S. rates are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

Measurements of relative sea level rise from tide gauges conflate the climatologically relevant increase in the volume of seawater with local vertical land motion. That latter, which varies from place to place, is

best measured using a Global Positioning System (GPS) station located near the tide gauge. It is driven by a range of processes that can be comparable to the climate signal and can locally exacerbate (subsidence/sinking) or mitigate (uplift) the risk of sea level rise (G Wöppelmann and M Marcos, 2016). Human activities triggering subsidence are often significant. They include soil drainage (e.g. for urban development purposes) and subsurface extraction of groundwater, oil, or gas.

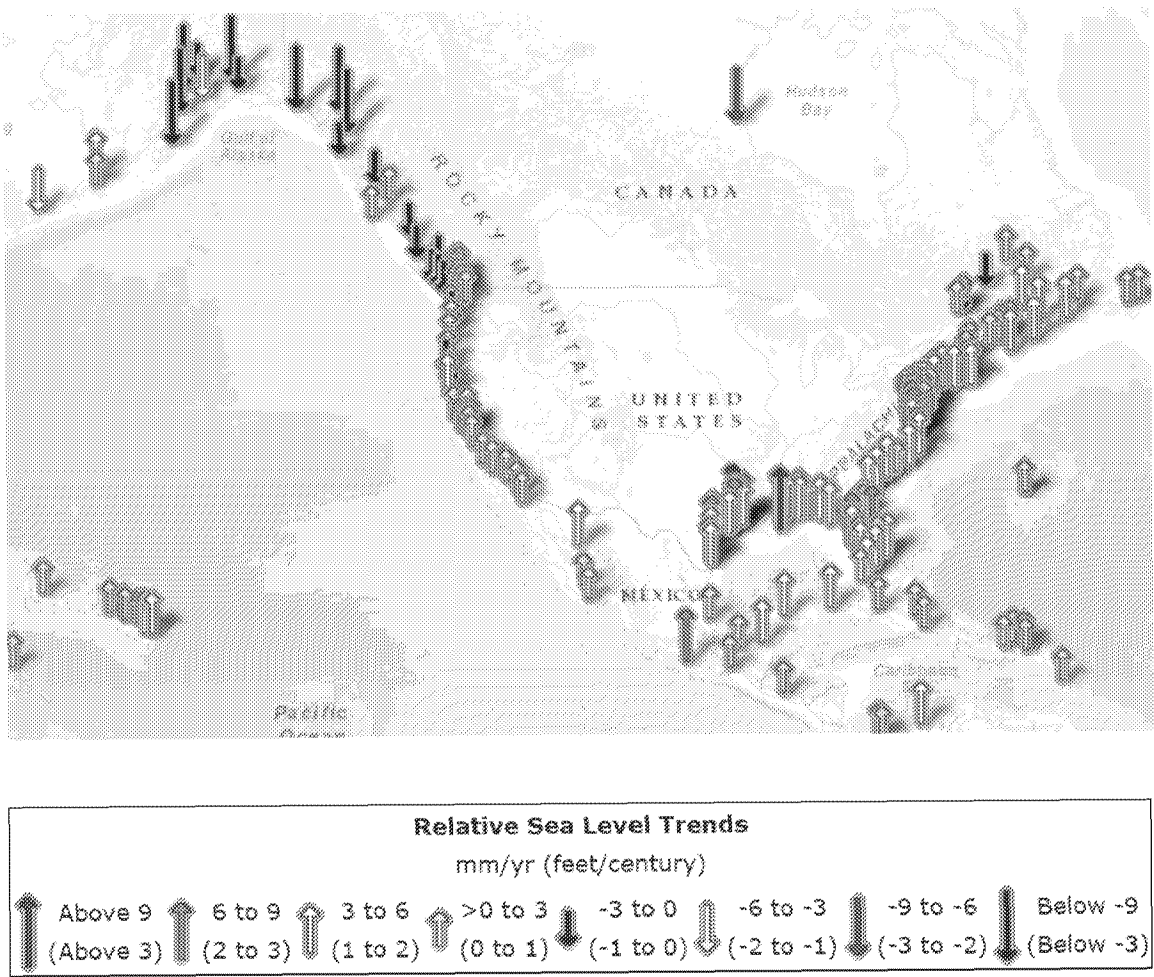


Figure 7.1. Map of rates of relative sea level rise along the U.S. coast (NOAA, <https://tidesandcurrents.noaa.gov/sltrends/>). For reference, 3 mm = 0.12 in.

Table 7.1 shows absolute sea-level rise (ASLR) for selected locations, determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR) (NOAA, 2025) and the vertical land motion (VLM) measurements (NAS, 2012; Letetrel et al., 2015; Karegar et al., 2016). The absolute sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local subsidence. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, Galveston, Grand Isle. For reference, the global average rate of absolute sea level rise is estimated to be 0.12 inches/year.

Location	RSLR	VLM	ASLR
San Francisco, CA	+0.08	-0.06	+0.02
Galveston, TX	+0.26	-0.19	+0.07
Grand Isle, LA	+0.36	-0.28	+0.08
St Petersburg, FL	+0.12	-0.02	+0.10
New York City, NY	+0.11	-0.05	+0.06

Table 7.1 Absolute sea level rise (inches/year) (Relative Sea Level Rise (RSLR) plus Vertical Land Motion (VLM))

San Francisco Bay

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.8 inches, at an average rate of 0.08 inches/year (Figure 7.2). As shown in Table 7.1, San Francisco’s vertical land motion is -0.06 inches/year (sinking), producing a recent absolute rate of +0.02 inches/year. Portions of Treasure Island, San Francisco International Airport, and Foster City are sinking as fast as 0.4 inches/year (M Shirzaei and R Bürgmann, 2018). Problems in the San Francisco Bay area, including threats to the airport, have been caused primarily by soil compaction in landfill zones that were formerly wetlands, not by the slow creep of global sea level rise.

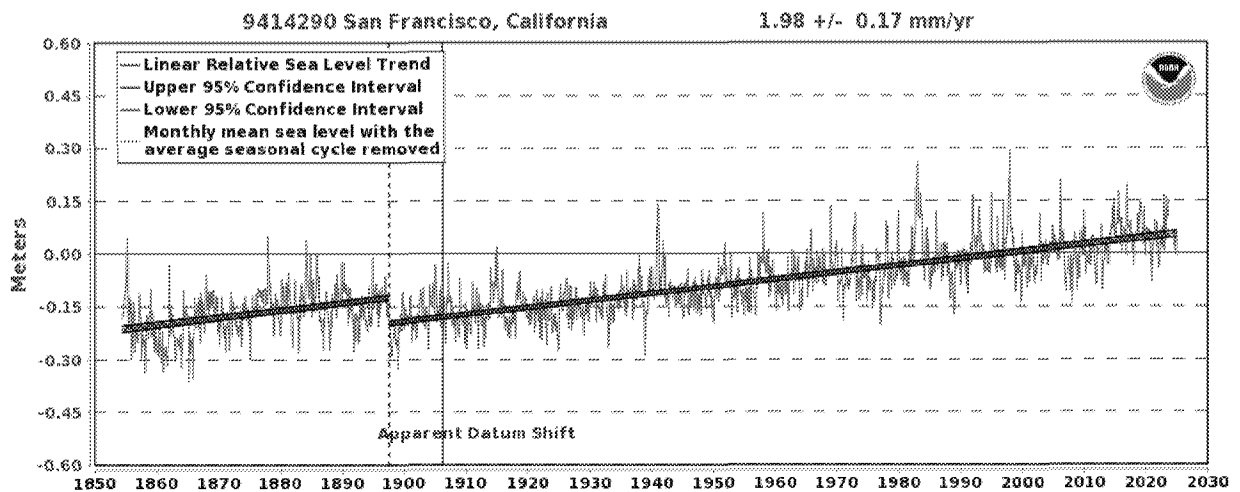


Figure 7.2. Tide gauge measurements at San Francisco, California, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290 (downloaded 4/22/25).

Galveston - Houston

Long-term tide measurements at Galveston Pier 21 show sea level rise of 2.18 feet in the past century, or a rate of 0.26 inches/year (Figure 7.3). Vertical land motion (subsidence) at Galveston is estimated at -0.19 inches/year, yielding an absolute rate of rise of +0.07 inches/year (Table 7.1). The U.S. Geologic Survey found that most of the land-surface subsidence in the Houston-Galveston region is a direct result of groundwater withdrawals (Kasmarek and Ramage), which caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 feet of subsidence had occurred in Houston.

Hurricanes have been the major concern in the region. The 1900 hurricane that struck Galveston and killed between 6,000 and 12,000 people is still considered the deadliest U.S. natural disaster (Weems, 2016). Hurricane Ike (2008) decimated large portions of the Bolivar Peninsula, literally removing significant portions of the land mass (UCS, 2017). While only 17 people were killed in Texas, property damage exceeded \$50 billion (White, 2017). In 2017, Hurricane Harvey struck the region, bringing catastrophic rainfall-triggered flooding that inflicted over \$125 billion in damages (NOAA, 2025).

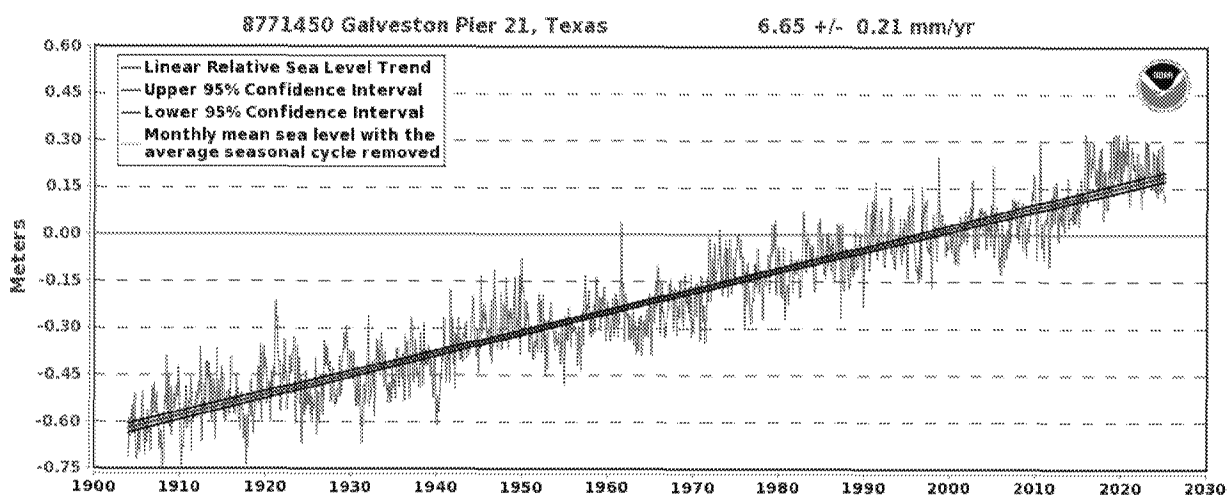


Figure 7.3. Tide gauge measurements Galveston Pier, TX, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450 (downloaded 4/22/2025).

New Orleans and the Mississippi delta

Long-term tide gauge measurements at Grand Isle, Louisiana, show that sea level has risen by slightly more than 3 feet over the last 100 years at an average rate of 0.36 inches/year (Figure 7.4). Vertical land motion (subsidence) is estimated -0.28 inches/year. Table 7.1 gives the absolute sea level rise as +0.08 inches/year.

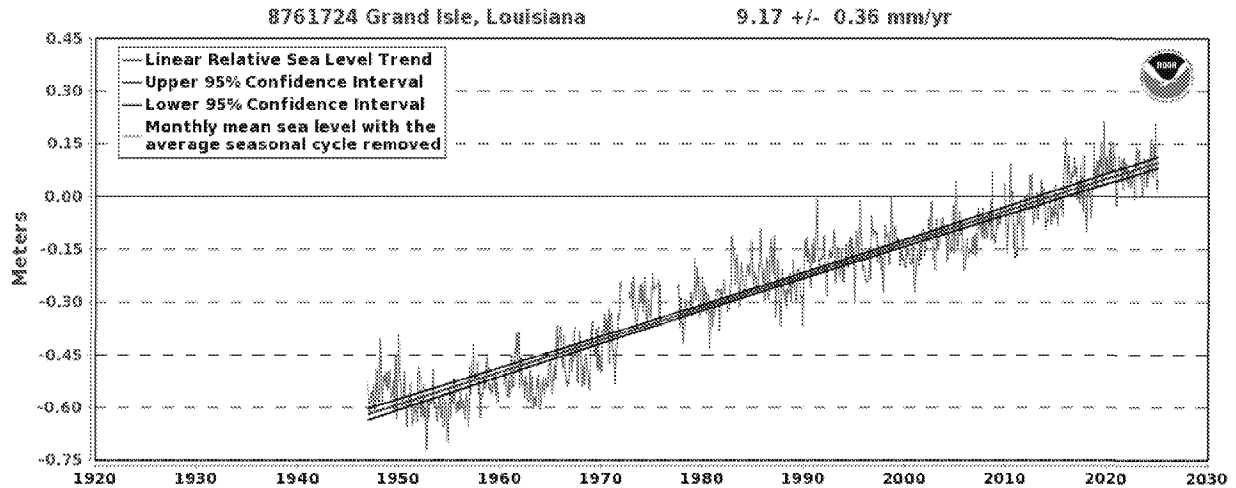


Figure 7.4. Tide gauge measurements at Grand Isle, LA, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724 (downloaded 4/22/25).

The issues of sea level rise and land loss in the Mississippi Delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi river being the dominant drivers. The construction of dams in the basin since the 1950s has decreased the Mississippi's suspended sediment load by ~50% (Malooney, 2018). A new subsidence map of coastal Louisiana finds the coastal region to be sinking at about one third of an inch per year (Neinhuis et al., 2017), associated with groundwater and resource withdrawal. As the city's elevation averages one to two feet *below* sea level, sea level rise from anthropogenic warming is hardly the dominant driver of New Orleans' problems.

New York City

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. Measurements by a tide gauge at the southern tip of Manhattan (The Battery) show that relative sea level has risen over 11 inches over the past century, at an average rate of 0.11 inches/year (Figure 7.5). But vertical land motion in the New York City area is -0.05 inches/year (roughly 5 inches per century), so that the absolute rate of sea level rise at The Battery is 0.06 inches/year, or about 55% of the measured relative sea level rise.

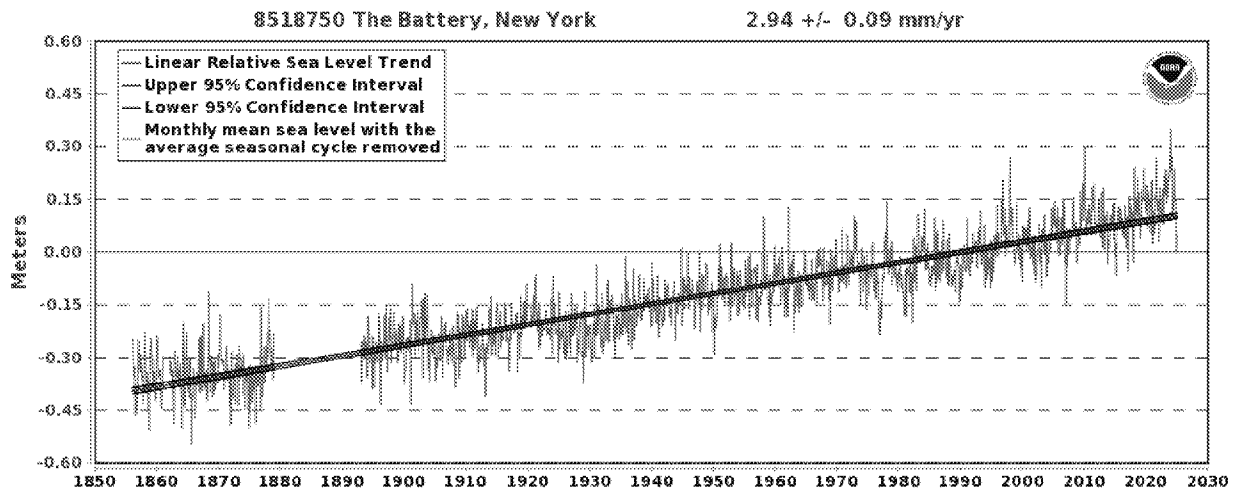


Figure 7.5. Tide gauge measurements at The Battery, New York, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (downloaded 4/22/25).

Following Superstorm Sandy, New York developed a comprehensive plan: [[HYPERLINK "http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf"](http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf)] (CNY,2013). A broad range of coastal protection measures are outlined that match the risks facing the various zones: increase coastal edge elevations, minimize upland wave zones, infrastructure to protect against storm surge, improve coastal design and governance, restore estuaries wetlands, coastal nourishment, site elevation, and drainage systems.

7.3 Projected sea level rise

The concern over sea level rise is not about the roughly 8 inches of global rise since 1900. Rather, it is about projections of *accelerated* rise based upon simulations of a warming climate through the 21st Century.

The IPCC AR6 finds *high agreement* across published global mean sea level projections for 2050 with little sensitivity to emissions scenarios. Considering only projections incorporating ice-sheet processes in whose quantification there is at least *medium confidence*, the global sea level projections for 2050, across all emissions scenarios, fall between 3.94 and 15.75 inches (5th–95th percentile *very likely* range) relative to the 1995–2014 baseline period (Fox-Kemper et al., 2021).

Conversely, AR6 states there is *low agreement* across published global mean sea level projections for 2100, particularly for higher emissions scenarios. Considering only projections representing ice sheet processes in whose quantification there is at least *medium confidence*, the AR6 global mean sea level projections for 2100 lie between 7.87 and 39.37 inches (5th–95th percentile *very likely* range) under the medium emissions scenario SSP2–4.5 (Fox-Kemper et al., 2021). There is deep uncertainty surrounding projections of sea level rise to 2100, particularly for the higher emissions scenarios.

In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the sea level rise has already occurred by 2025. From the tide gauge measurements in Figures 7.2-7.5, there is no obvious acceleration in sea level rise beyond the historical average rate of sea level rise.

In February 2022, NOAA issued its projections of sea level rise for various sites along the US coast (Sweet et al, 2022). They claim that by 2050, the sea will have risen one foot at The Battery in Manhattan. A one foot rise in thirty years would be more than twice the current rate and about three times the average rate over the past century. In that historical context, NOAA's projection is remarkable—as shown in Figure 7.6, it would require a dramatic acceleration beyond anything observed in the early 20th century. But even more noteworthy is that they say this rise is “locked in”—it will happen no matter what future emissions are. We should know in a decade or so whether that prediction has legs.

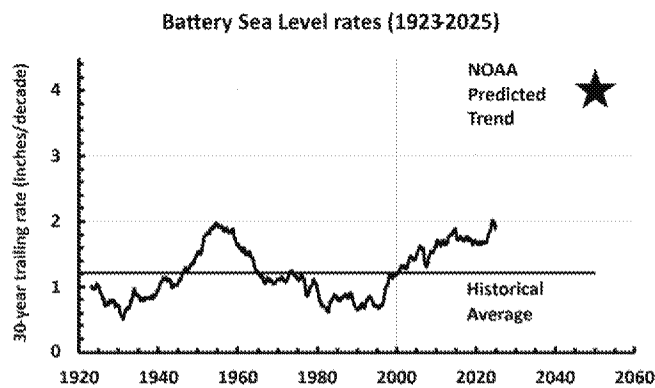


Figure 7.6 Rate of sea level rise at the Battery in Manhattan. Shown is the historical thirty-year trailing trend, together with the allegedly “locked in” NOAA predicted trend for 2050. Historical data: NOAA Tides and Current.

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8 UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION

Chapter summary

“Attribution” refers to determining cause regarding some aspect of climate change, specifically with reference to anthropogenic activity. There is an ongoing scientific debate around attribution methods, particularly regarding extreme weather events. Attribution is made difficult by high natural variability, the relatively small expected anthropogenic signal, lack of high-quality data, and reliance on deficient climate models. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

Substantive criticism of the main IPCC assessments of the role of CO₂ in recent warming focus on inadequate assessment of natural climate variability, uncertainties in measurement of solar variability and aerosol forcing, and problems in the statistical methods used for attribution.

The IPCC does not in general make attribution claims for most climate impact drivers related to extreme events. Statements related to statistics of global extremes (e.g. event probability or return times, magnitude and frequency) are not generally considered accurate owing to data limitations and are made with low confidence. Attribution of individual extreme weather events is challenging due to their rarity. Conflicting claims about the causes of the 2021 Western North America Heatwave illustrate the perils of hasty attribution claims about individual extreme events.

8.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of its cause. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

Detection: “Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.”

Attribution: “Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.”

Both steps rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible, attribution requires statistical inference to assess how much human activities, such as GHG emissions, versus natural factors, like volcanic eruptions, contribute to observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially those for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. AR4 Working Group I (Hegerl et al., 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

AR5 Working Group II (Cramer et al., 2014) makes the following statement:

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

8.2 Attribution methods

The IPCC employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key methods that have been used by the IPCC.

Optimal Fingerprinting uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

Time Series Analysis exploits statistical differences between anthropogenic forcing and natural variability to see which dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

Process-Based Attribution focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

Extreme Event Attribution assesses the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals

- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings might have modified those processes

8.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.” (IPCC, 2007)

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period.” (IPCC, 2013)

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.” (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20th century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC’s assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The last is discussed in Chapter 6, while this chapter discusses the first two factors. All of these criticisms are relevant to the IPCC’s policy-informing attribution of the recent warming, which also underpins extreme event attribution

8.3.1 Natural climate variability

IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average having essentially no net impact on the warming since 1850-1900. As discussed below, this minimal contribution of natural variability has been disputed by several publications that question the magnitudes of solar variability and internal variability from large-scale ocean circulation.

Solar variability

IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small (0.05 W/m^2 , Myrhe et al., 2014). IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by $0.7\text{--}2.7 \text{ W/m}^2$, a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While AR6 shows a substantially greater solar impact than does AR5, the overall impact on the climate was still assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate - something that is not evident from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

The change of TSI over time remains a challenging problem.. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used to calibrate proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990's, before a decline in the early 21st century; this period is often termed the “Modern Maximum.” (Chatzistergos et al., 2023; Solanki et al., 2004; Usoskin et al., 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, either amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. There are numerous candidate processes, including solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Such solar indirect effects are not included in climate models, although indirect methods of estimating their impacts suggest they are significant. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

Natural variability of large-scale ocean circulations

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns, including the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Nino-Southern Oscillation (ENSO). These circulations influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, most models show have too little amplitude compared to observations at multi-decadal frequencies and phasing out-of-sync with the observed climate (Kravtsov et al. 2024). Averaging multiple simulations effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO₂ forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

“Decadal variability in the Pacific, associated with the PDO or IPO [Interdecadal Pacific Oscillation], contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.” (IPCC, 2013)

“Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (*high confidence*).” (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the past 50 years, when most of the recent warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The time series of global surface temperature anomalies since 1850 (Figure 8.1) shows irregular variations of significant amplitude against the background of an overall warming trend and, after 1976, a pronounced difference in trends between the Northern Hemisphere and the Southern Hemisphere. The period between 1905-1945 shows a strong trend of warming. The following thirty years from 1945-1976 showed slightly declining temperatures. The most recent warming period started in 1977.

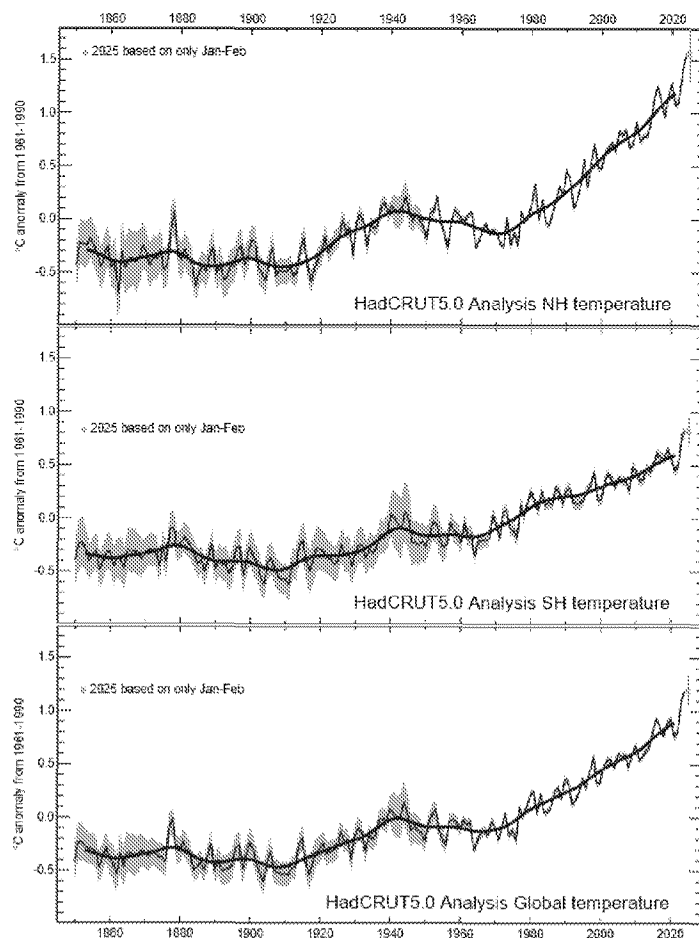


Figure 8.1 Global average surface temperature anomalies 1850—2025. Top: Northern hemisphere. Middle: Southern hemisphere. Bottom: Global average. Source: UK Hadley Centre [[HYPERLINK "https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf"](https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf)]

The causes of the early 20th century warming are discussed by Hegerl et al. (2017; 2019). The atmospheric CO₂ concentration increased from 298 ppm in 1905 to 310 ppm in 1941; hence this implies that CO₂ had little impact on the warming. Volcanic activity during this period was very low, and solar forcing is uncertain. Hegerl et al (2017) somehow inferred that 40-54% of this warming could be attributed to external forcing, with the rest associated with internal variability. Bronniman et al (2024) focused on the causes of the cooling in the first decade of the 20th century in the Southern Hemisphere. They found that the cooling was related to a La-Niña-like pattern in the Pacific, a cold tropical and subtropical South Atlantic, a cold extratropical South Pacific, and cool southern midlatitude land areas. The Southern Annular Mode was positive, with a strengthened Amundsen–Bellingshausen seas low, although the spread of the data products is considerable.

The warming in the 1930's and subsequent cooling during mid century was particularly pronounced in the Arctic. Bokuchava and Semenov (2021) find that most likely these variations were caused by a combined effect of long-term natural climate variations in the North Atlantic and North Pacific with a contribution of the natural radiative forcing related to the reduced volcanic activity and variations of solar activity as well as growing greenhouse gases concentrations. Tokinaga et al (2017) showed that the combined effect of internally generated Pacific and Atlantic interdecadal variability intensified Arctic

warming in the early 20th century. The synchronized Pacific-Atlantic warming drastically alters planetary-scale circulations over the Northern Hemisphere; these same circulation patterns have a global influence.

The cooling period between 1945 and 1976 has been referred to as the “grand hiatus.” Numerous causes have been hypothesized: natural internal variability from fluctuations associated with the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation; cooling from increased emissions of aerosols from industrial activities; increased heat uptake in the Atlantic, Southern and Equatorial Pacific Oceans. Thompson et al. (2010) find that the hemispheric differences in temperature trends in the middle of the twentieth century stem largely from a rapid drop in Northern Hemisphere sea surface temperatures of about 0.3 °C between about 1968 and 1972.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Niño and La Niña events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming. When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, 40 percent or more of the warming in the second half of the 20th century is attributed to natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

8.3.2 *Optimal fingerprinting*

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or “fingerprints”) associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of “signals”, which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares. The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be “detected”. If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the research literature. While it has been widely used and prominently featured by the IPCC since 2001 there is very little literature examining the statistical properties of the results it generates. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

A series of papers by McKittrick (McKittrick 2022a, 2022b, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that practices adopted from econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2022a) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent fingerprinting coefficients, undermining the reliability of the method. Chen et al. (2023) confirmed this analysis and argued that the method could yield unbiased results but only under very stringent assumptions. McKittrick (2022b) and (2023) raised a further concern that climate scientists—virtually alone

among scientific disciplines—have used an estimation method called Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions that easily arise in optimal fingerprinting, TLS yields estimates with large positive biases. Thus, any study that used TLS for optimal fingerprinting without verifying its applicability in the specific data context has likely overstated the result.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics that are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which is consistent with the estimate by Lewis (2022) using a different estimation method and multiple independent data sets.

While these analyses do not falsify all results stemming from the IPCC optimal fingerprinting method, they do challenge the basis on which they were believed to be correct.

8.3.3 Time series methods

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. These have the advantage of not depending on assumptions about the accuracy of climate models, but the disadvantage that they depend on difficult-to-test assumptions about the data generating process underlying climate and forcing data. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades et al., 2016, Balcombe et al., 2019, Dagsvik et al., 2020, Razzak, 2022, Dagsvik and Moen, 2023).

“Granger causality” modeling is a tool for determining directions of influence in data series that move together. It is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to the well-known Vostok ice core data revealed an error in Al Gore’s documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO₂ changes over a 440,000 year span, which he asserted was due to CO₂ driving temperature changes. But temperature changes can also affect atmospheric CO₂ levels. Davidson et al. (2015) examined the series and found that temperature Granger causes CO₂ but not the reverse. In other words on the time scales represented in the Vostok data the coherence in the series is primarily due to the influence of temperature on CO₂ levels not the feedback of CO₂ levels on temperature.

In summary, the primary statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently

been criticized as inherently biased. Time series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

8.4 Declining planetary albedo and recent record warmth

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also changed abruptly in recent years. The question to be answered is whether the change is an internal feedback to warming caused by greenhouse gases or whether something else changed the fraction of absorbed radiation which then caused the recent warming.

The albedo is the fraction of incoming solar radiation that is reflected back into space rather than being absorbed by the planet. Highly reflective surfaces like cloud tops and snow and ice are most important in this regard. The Earth's albedo is approximately 30%, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed by the planet to be then re-radiated as heat. Hence, other things being equal, a decline in albedo is associated with a warming of the Earth.

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure 8.1 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m² in solar energy averaged over the planet (Hansen and Karecha, 2025). For comparison, the IPCC estimate of forcing from the increase in atmospheric CO₂ compared to preindustrial times is approximately 2.2 W/m² (Figure 3.1.2).

Looking back prior to 2000 with less adequate data, Gossling et al. (2025) assessed that planetary albedo was relatively low around the 1940's and 50's, before rising industrial aerosol precursor emissions increased albedo until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum may have been the lowest since at least 1940.

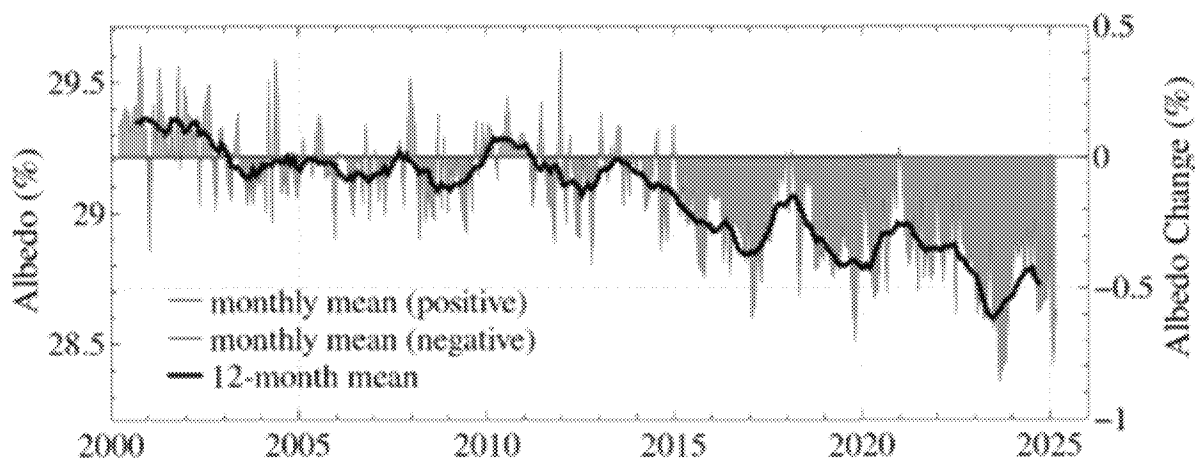


Figure 8.1. Earth’s albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface characteristics can’t explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5% since 1980 (https://nsidc.org/data/seaice_index/images/s_plot_hires.png), although following 2007 there has been a pause in the Arctic sea ice decline (England et al., 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that “There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability.” (SPM, A.1.5)
- Northern hemispheric annual snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer.
[HYPERLINK "<http://climate.rutgers.edu/snowcover/>"]
- Global greening (Chapter 2) is contributing to the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo increase associated with increasing forested area.

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

This leaves the most likely explanation for the sharp albedo decline as changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (e.g dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall may be producing less dust. For anthropogenic aerosols, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth’s radiation balance (Hodnebrog et al., 2024; Yuan et al., 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

This leaves changes in clouds as the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb et al., 2024; Gosling et al 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb et al. found that decreases in low and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the Northern hemisphere, whereas in the Southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones. Gossling et al. (2025) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

The question then becomes what caused the change in cloud cover. Two causes have been posited for the declining cloud cover over the past decade:

- Natural climate variability
- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

The existence of a new positive low cloud feedback that began emerging in 2015 is not easy to justify. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was the strongest El Nino event on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al., 2017; Arthun et al. 2021).
- The Pacific Decadal Oscillation (PDO) positive index peaked in 2016, then declined and has been in negative territory since late 2019
- Eruption of the submarine Hunga-Tonga volcano in 2022

Interannual cloud anomalies associated with the El Nino Southern Oscillation (ENSO) have a significant global signal and strong regional signals especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Gossling et al. (2025) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere, in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz et al, 2025; Kuchar et al., 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of Hunga Tonga eruption on planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1 to 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO₂. While it is difficult to untangle causes of the trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and also the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming, or a temporary fluctuation driven by natural variability

8.5 Attribution of climate impact drivers

The IPCC (Ranasinghe et al. 2021) defines “climate impact drivers” or CIDs as “physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems.” Hence CIDs are those features of the weather and climate system of primary interest in assessing the impacts of climate change since they potentially affect humans and the natural world. For instance, under the heading “Heat and Cold” CIDs are identified as mean air temperature, extreme heat, cold spells and frost. The IPCC also points out that CIDs are not necessarily harm-related: depending on the system in question they can be detrimental, neutral, beneficial or a combination.

The first column of Table 12.12 in Ranasinghe et al. (2021, p. 1856), reproduced here as Table 8.1, summarizes the AR6 assessment of whether a signal of attributable anthropogenic influence has emerged across all major CIDs. One of the themes of this chapter is that attribution methods used by the IPCC tend to overstate the anthropogenic influence and understate the role of natural variability. Nonetheless a striking feature of that summary table is how few CIDs exhibit an anthropogenic signal sufficient to distinguish them from natural variability.

Climatic Impact-driver Type	Climatic Impact-driver Category	Already Emerged in Historical Period
Heat and Cold	Mean air temperature	1
	Extreme heat	2
	Cold spell	4
	Frost	
Wet and Dry	Mean precipitation	
	River flood	
	Heavy precipitation and pluvial flood	
	Landslide	
	Aridity	
	Hydrological drought	
	Agricultural and ecological drought	
	Fire weather	
Wind	Mean wind speed	
	Severe wind storm	
	Tropical cyclone	
	Sand and dust storm	
Snow and Ice	Snow, glacier and ice sheet	
	Permafrost	
	Lake, river and sea ice	11
	Heavy snowfall and ice storm	
	Hail	
	Snow avalanche	
Coastal	Relative sea level	
	Coastal flood	
	Coastal erosion	
Open Ocean	Mean ocean temperature	
	Marine heatwave	
	Ocean acidity	
	Ocean salinity	13
	Dissolved oxygen	14
Other	Air pollution weather	
	Atmospheric CO ₂ at surface	
	Radiation at surface	

High confidence of decrease	Medium confidence of decrease	Low confidence in direction of change	Medium confidence of increase	High confidence of increase
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Table 8.1: Reproduction of column 1 of Table 12.12, IPCC AR6 Working Group I report. Emergence of anthropogenic signal in historical period for CIDs shown. White: no signal detected. Blue and orange: change detected (decrease or increase) and confidence level as indicated in color legend.

Out of the 33 weather impact categories an anthropogenic signal is asserted with *high confidence* in only five, and with *medium confidence* in a further four. (Note that one of the CIDs is an increase in CO₂ levels, and since it is a tautology to attribute this to increased CO₂ levels this CID can be ignored.) For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the five *high confidence* assertions, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Also two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, drought etc.

Columns 2 and 3 of IPCC Table 12.12 report on whether anthropogenic signals are expected to emerge this century under RCP8.5, the most extreme forcing scenario. We have omitted these columns for several reasons. First, because they refer to whether climate models project detectable signals in the observations, which is a very different question than our concern here, whether a signal has been detected in historical data. Second, as we discuss in Chapter 4, the RCP8.5 scenario is a misleading and implausible high-end storyline, it is not a “base case” or business-as-usual projection. Third, the ensemble of detailed models is acknowledged (Palmer and Stevens 2019) to be “not fit for purpose” in describing regional changes and “unable to represent future conditions at the degree of spatial, temporal, and probabilistic precision with which projections are often provided.” (Nissan et al, 2019)). Even with these caveats, we note that the omitted columns in AR6 Table 12.12 indicate most weather impacts are not expected to exhibit an anthropogenic signal this century.

As we discussed in Chapter 7 natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time. Table 8.1 makes the related point that, again contrary to popular belief, attribution of changes in most extreme weather types to human influence is not currently possible. Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather.

Citations Palmer [[HYPERLINK "https://www.pnas.org/doi/full/10.1073/pnas.1906691116"](https://www.pnas.org/doi/full/10.1073/pnas.1906691116)]

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8.6 Extreme event attribution (EEA)

Examining the IPCC’s treatment of extreme weather and climate event attribution more broadly, the AR6 provides an ambiguous assessment of the role of anthropogenic warming that differs between chapters. Chapter 11 of WG1 states (Seneviratne et al., 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, as noted above, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of particular extreme weather events. The most prominent effort is World Weather Attribution (WWA; worldweatherattribution.org), an international research initiative for extreme event attribution that purports to analyze how climate change influences the likelihood and intensity of extreme weather events. Their approach is to use large ensembles of regional climate models to compare the event in today's climate with a counterfactual pre-industrial climate without human influences.

WWA has a prominent public presence in linking extreme weather to climate change, with its press releases attracting considerable attention in public and policy discussions. However, the WWA's extensive promotion of non-peer-reviewed findings, its funding ties, its open admission to shaping analyses to serve litigation, and its methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of their conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to influence climate science and media narratives. Technical criticisms of the approach include a lack of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by greenhouse gases; and a failure to adequately account for internal climate variability.

Because EEA is relatively new many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 7, many of the worst extreme weather and climate events in U.S. history occurred prior to the first half of the 20th century including in the early 19th century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean that a climate change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an “ordinary” weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second “heatwave” regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh et al. (2015) both point out that different distributions may fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis drawing a connection between individual events and global climate change should be avoided. Furthermore, the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al., 2020). Methods to eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison 2023) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain it should be avoided altogether.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

We provide a case study of a recent high impact extreme event in the U.S. to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

8.6.1 Case study – 2021 Western North America heat wave

The 2021 Western North America heat wave was an extreme event that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA team generated international headlines with their analysis, which provided the following attribution statements (WWA, 2021; Philip et al., 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today’s climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important counter to the first claim is that other researchers concluded from historical weather data that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman, 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman, 2023, p. 49).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking mid-tropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking mid-tropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using

a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

Bercos-Hickey et al. (2022) conducted a statistical analysis of a model-based attribution study of this heat wave. Because the event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave - they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analyses showed that the event was caused by rare meteorological conditions that were not made more probable by global warming.

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PART III: IMPACTS ON ECOSYSTEMS AND SOCIETY

9 CLIMATE CHANGE AND US AGRICULTURE

Chapter summary

There is abundant evidence going back decades that rising CO₂ levels benefit plants, including agricultural crops, and that CO₂-induced warming will be a net benefit to US agriculture. The warming since 1981, in combination with adaptive behavior by farmers, has been beneficial for maize. The increased ambient CO₂ has also boosted productivity of all major US crop types. Various attempts to argue that CO₂-induced warming will harm agriculture do not hold up under scrutiny.

9.1 Econometric analyses

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should be capitalized into higher market values for agricultural land, and vice versa. While individual crops might benefit from or be harmed by climate change, once the adaptive responses of farmers are considered the value of farmland represents an index of whether the changes are expected to be beneficial or not. Mendelsohn et al. (1994) examined the relationship between historical climatic variations on agricultural land values and concluded global warming would be slightly beneficial to American agriculture.

The Mendelsohn et al. method, called Ricardian analysis after David Ricardo, the 19th century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached conclusions similar to Mendelsohn et al. (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the US agricultural sector. However, a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in US agriculture due to climate warming.

Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and

20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

A major deficiency of all these studies, however, is that they omit the role of CO₂ fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO₂. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO₂ that drives them. As explained in Chapter 2 CO₂ is a major driver of plant growth, so this omission biases the analysis towards underestimation of the benefits of climate change to agriculture.

9.2 Field studies of CO₂ enrichment

One of the ways the effect of CO₂ on crop growth has been studied is through “free air enrichment experiment” or FACE plots, in which small sources of CO₂ are placed in fields surrounding plants and the growth response to elevated CO₂ under varying weather conditions are recorded. Ainsworth et al. (2020) summarizes results from about 250 such studies. They found that elevation of CO₂ by 200 ppm caused an average 18% increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO₂ on all kinds of plant growth. Here we review some of the results on key US agricultural crops.

Soybean

Studies on the impact of elevated CO₂ on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO₂ concentrations improved photosynthesis rate, water use efficiency, and growth (Li, 2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. There were also ten studies reporting on +600 ppm CO₂ enrichment, which increased photosynthesis by an average of 90.3%.

Maize (corn)

The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO₂. An experimental study (Allen Jr, 2011) exposed plants to water stress conditions in sunlit controlled-environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO₂. The drought stress caused a 41% loss of growth under ambient CO₂ but only a 13% loss under elevated CO₂.

Wheat

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO₂ levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured both the yield and nutritional quality of an “improver” hybrid wheat variety and its parents under elevated CO₂ levels (+166 ppm). They reported

a grain yield increase of +16% but a 7% decrease in grain protein levels. But they found that the food quality of different wheat varieties responded differently to elevated CO₂ levels, so that with proper varietal selection, growers could select wheat types that best take advantage of the elevated CO₂.

Further evidence

A 2021 report from the US National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO₂ levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO₂ emissions had boosted U.S. crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been estimated using FACE experiments. They found that every ppm of increase in CO₂ concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.

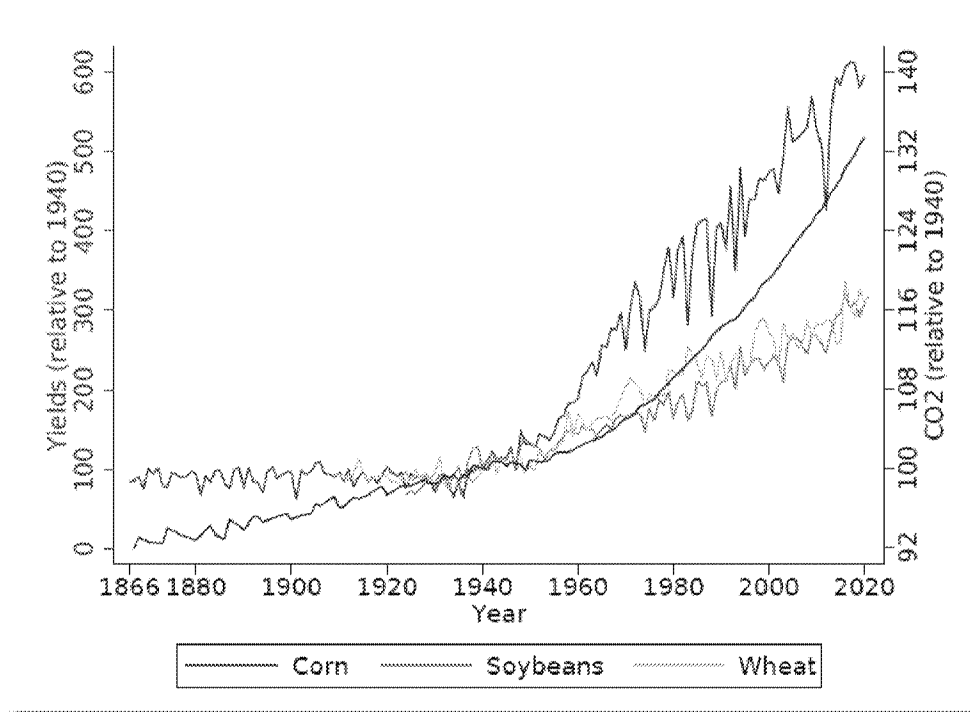


Figure 9.1: US average CO₂ levels and yields of corn, soy and wheat all normalized so 1940=100.
Source: Taylor and Schlenker (2021)

Beyond growth benefits, extra CO₂ boosts plant resilience to dryness. Derying et al. (2016) surveyed evidence on crop water productivity (CWP, the yield per unit of water used), drawing attention to the potential for CO₂ both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO₂ fertilization predicted CWP losses but CO₂ fertilization more than offset them; once fertilization was taken into account,

all regions showed a net CWP gain. Deryng et al also reported that negative yield impacts on wheat and soybean were fully offset by CWP gains, and mitigated by up to 90% for rice and 60% for maize.

Similar to this, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO₂ uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, observations show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO₂ levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

9.3 Crop modeling meta-analyses

Notwithstanding the abundant evidence for the direct benefits of CO₂ and of CO₂-induced warming on crop growth, in 2023 the US Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based in large part on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore et al., 2017). One of the two damage models used by the EPA attributed nearly half of the 2030 SCC to projected global agricultural damages based on the Moore et al. (2017) analysis. This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. Moore et al. projected declining global crop yields for all crop types in all regions due to warming.

McKittrick (2025) re-examined the Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries ($N=862$) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the variable most commonly missing was the change in ambient CO₂ and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables. He thereby increased the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 10.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).

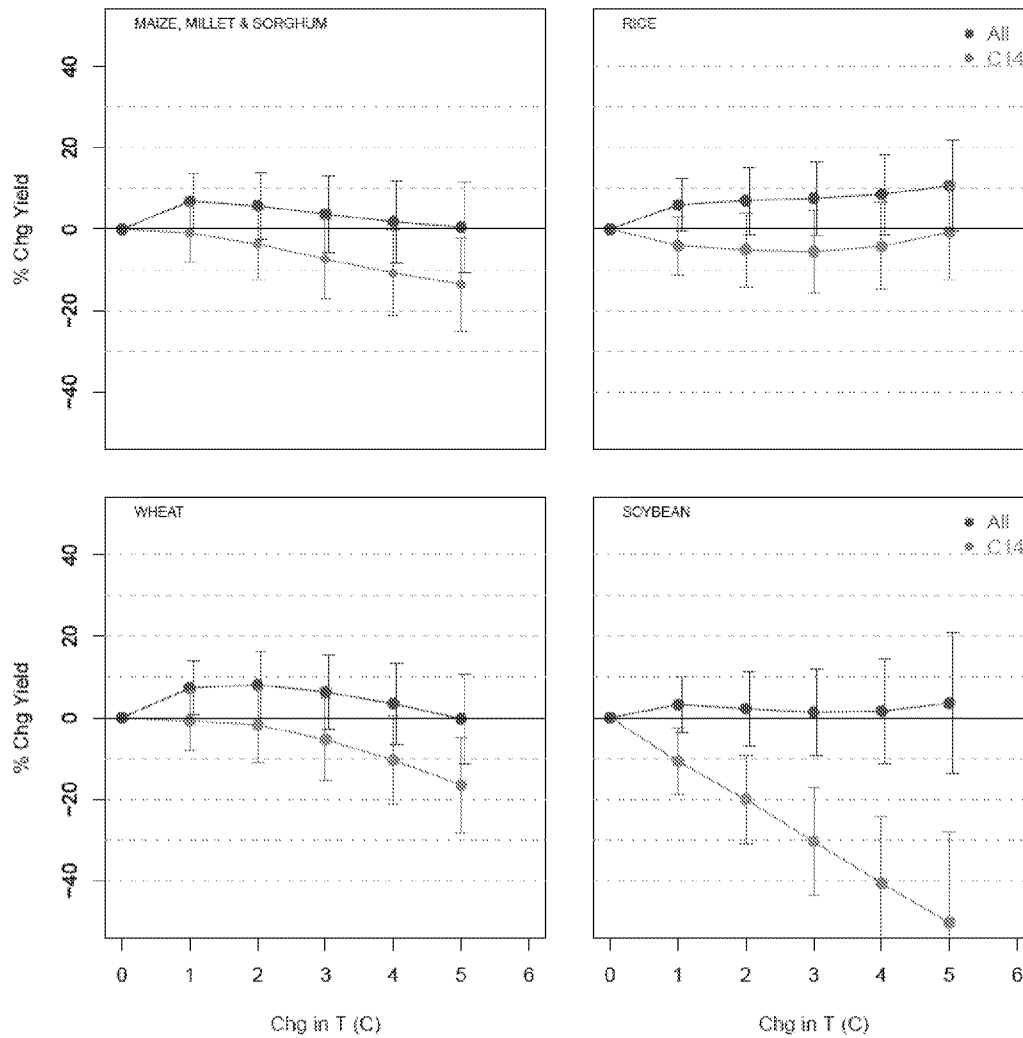


Figure 9.2 Crop yields under CO₂-induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).

In summary, there is abundant evidence going back decades that rising CO₂ levels benefit plants including agricultural crops, and that CO₂-induced warming will be a net benefit to US agriculture.

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10 MANAGING RISKS OF EXTREME WEATHER

Chapter summary

Trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. U.S. mortality risks even under extreme warming scenarios are not projected to increase as long as people are able to undertake adaptive responses.

10.1 Socioeconomic context

Risks from human-caused climate change are affected by natural weather and climate variability, and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as US population grew from 76 million in 1900 to over 331 million in 2020 (Goklany, 2011). For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01% of the US population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006% of the US population) (NOAA, 2025; USCB, 2025).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify (Deryugina and Hsiang, 2023). US weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation (NRC, 2010). Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B (NBER, 2024).

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992) have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes (FEMA, 2020). Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012) (BMI, 2013). Inland dams in the US help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers (TVA, 2025). During Hurricane Helene (2024), TVA's strategies prevented approximately \$406M in potential damages (APPA, 2024).

10.2 Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and

other government officials have cited the upward trend in the Billion Dollar Disaster series as evidence that climate change is making extreme weather worse (Pielke Jr., 2024). But over time, population and wealth have increased dramatically in the US, so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. Pielke Jr. (2024) demonstrates that losses per weather disaster as a proportion of GDP have decreased by about 80% since 1980, as shown in the figure below. Pielke Jr. (2024) also argued that in addition to relying on opaque data sources and unreported adjustments, NOAA failed to normalize its Billion Dollar Disaster data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from publication (Pielke Jr., 2025).

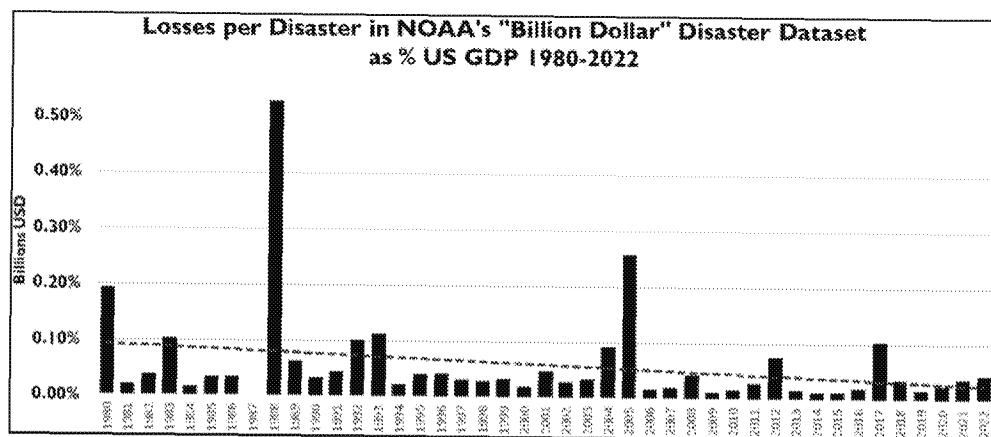


Figure 10.1: Losses per disaster in NOAA’s billion dollar disaster dataset (the version downloaded in July 2023), 1980 to 2022. Source: (Pielke, Jr. 2024)

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. And finally, the US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages.

10.3 Mortality from temperature extremes

10.3.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. It stands to reason that extreme heat events would likely become more frequent while extreme cold events would become less frequent. This pattern is evident in the historical period though not in the continental US (Chapter 6) and is expected to continue with further warming.

Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes is typically caused by hypothermia and heart strain. Global mortality is substantially greater for cold conditions than for hot conditions (Zhao et al 2021, Ritchie 20214). Unlike with heat-related mortality. Cold-weather risks set in even at moderately cold conditions (Gasparini et al. 2015, Lee and Dessler 2023). A 13-country study of 74 million deaths from 1985 to 2012 estimated that, on average, 7.7% of deaths were attributable to sub-optimal temperatures, of which 7.4% were attributable to cold and only 0.4% were attributable to heat (Gasparini et al. 2015). In other words cold weather killed 18.5 times as many people as did hot weather.

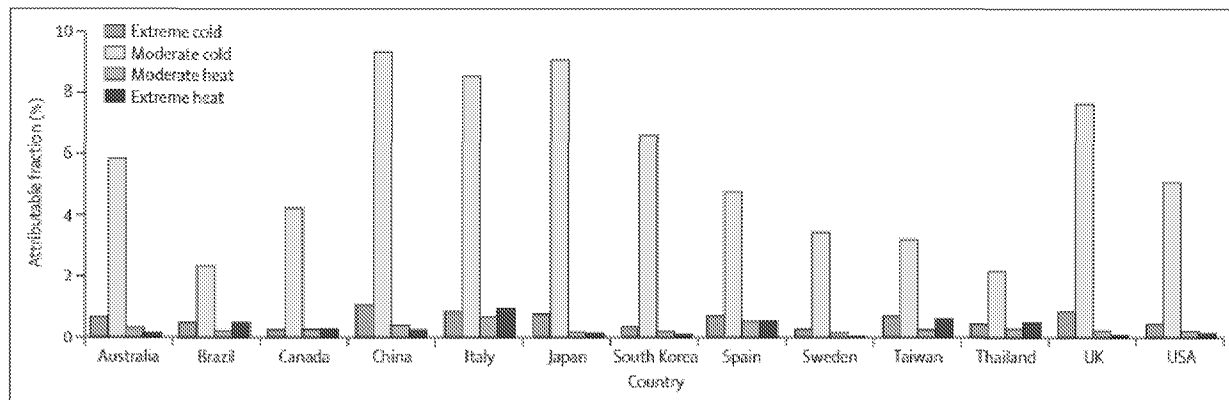


Figure 10.3.1. Mortality attributable to extreme and moderate cold and heat by country. Source: reproduced from Gasparini et al. (2015).

Figure 10.3.1 shows the distribution of results from Gasparini et al. (2015) by country. For the United States the fraction of deaths attributable to temperature was 5.9%, of which 5.5% was due to cold, thus cold weather killed 14 times as many people as hot weather.

The US EPA reports that, after adjusting for seasonality, the cold-related death rate in the U.S. ([[HYPERLINK "https://www.epa.gov/climate-indicators/climate-change-indicators-cold-related-deaths"](https://www.epa.gov/climate-indicators/climate-change-indicators-cold-related-deaths) \t "_blank"]) is about twice as large as the heat-related rate (see [[HYPERLINK "https://www.epa.gov/climate-indicators/climate-change-indicators-cold-related-deaths"](https://www.epa.gov/climate-indicators/climate-change-indicators-cold-related-deaths)] and ([[HYPERLINK "https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths"](https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths) \t "_blank"])).

There is strong evidence that people adapt to weather risks. Lee and Dessler (2023) reported that 86% of temperature-related deaths across 40 cities in the U.S. were due to cold-related mortality, and that due to adaptation the relative risk of death declined in hot and cold cities alike as seasonal temperatures increased. Allen and Sheridan (2018) found that short, early-season cold events were 2 to 5 times deadlier than hot events, but the mortality risk of both cold and hot extremes drops to nearly zero if the events occur late in the season.

Davis et al. (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb et al. (2014) examined mortality data for 106 million people in over 100 cities U.S. cities and found a 60% decline in average heat-related mortality over the period 1987—2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million

deaths in 211 U.S. cities from 1962 to 2006. Nordio et al. (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, by reducing mortality from cold events rising temperatures are associated with a net saving of lives.

The IPCC AR6 Working Group 2 Chapter 16.2.3.5 (O'Neill et al. 2022) acknowledges that heat-related mortality risk is declining over time:

“Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.”

It is both disappointing and telling to see how the IPCC misrepresents the situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

The observed decline in US heat-related mortality has been specifically attributed to adaptation. Wang et al. (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live Wang et al. project not only no increase in heat-related mortality but an overall decrease for the US as a whole. They conclude that

“Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves... Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.”

10.3.2 Mortality risks and energy costs

A 2016 study of US long term mortality risks associated with temperature variations (Barreca et al. 2016) showed that increases in mortality across the US are associated both with cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus et al. (2022) showed that wealthy and poor households in the US adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels ($< 5^{\circ}\text{C}$) energy spending in high-income households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days ($> 30^{\circ}\text{C}$) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

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11 CLIMATE CHANGE, THE ECONOMY AND THE SOCIAL COST OF CARBON

Chapter summary

Economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the AR5. Mainstream climate economics has recognized that CO₂-induced warming may have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO₂ emissions or find poor countries as likely to benefit from it as rich countries.

Social Cost of Carbon (SCC) estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC (i.e. a social benefit of emissions). The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions. Consideration of potential tipping points at present does not justify major revisions to SCC estimates.

11.1 Climate change and economic growth

11.1.1 Overview: climate is a relatively minor issue for a modern economy

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus, 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society always adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued that any effects of climate change on US economic activity would be small relative to the many other changes that would happen.

... Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.

It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. ...

I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.

(Schelling 1992, emphasis added)

Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report:

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers. Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.

(Arent et al. 2014, emphasis added)

That statement is validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty!

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen, 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr, 2018, 2020) as have mortality risks (Formetta and Feyen, 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKittrick, 2015). Nor have past extreme weather events had a significant effect on US banks' performance (Blickle et al., 2021). The following chart is illustrative:

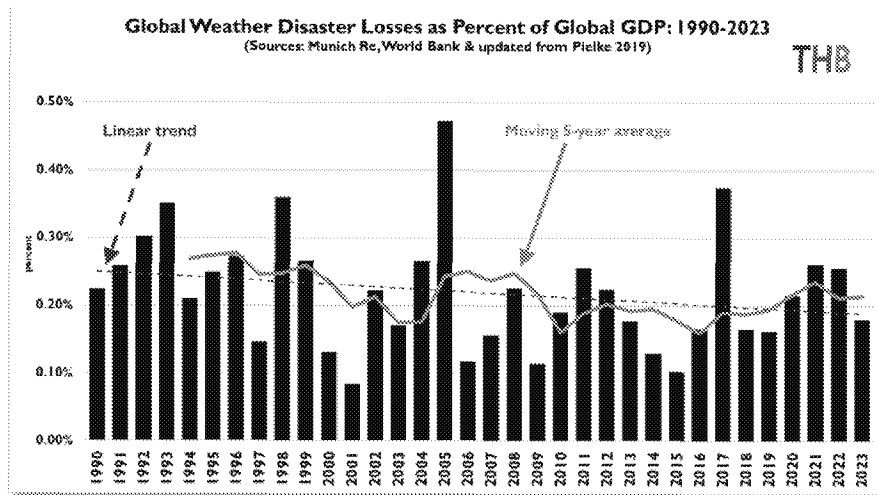


Figure 11.1 Global weather losses as a fraction of GDP. Source: Pielke Jr. (2023)

For these reasons, economists have long been reluctant to endorse attempts to “stop” climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it:

Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it... The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.

(Storm 2017)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future, 2025). Nordhaus’ work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus, 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the time of Nordhaus’ Nobel Prize award was described in Nordhaus (2018); it had a climate sensitivity parameter of 3.1°C for CO₂ doubling, consistent with the best estimate in contemporary IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only \$0.4T in global abatement costs and leads to \$134.2T (trillion dollars) in global climate damages for a total cost of \$134.6T. The climate model component of DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models.

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we modestly scale back fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO₂ emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of \$177.8T, which is \$43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even worse.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

11.1.2 Empirical analysis of climate change and economic growth

Many other studies have used econometric methods applied to historical data, instead of IAMs, to study the potential impact of climate change on economic growth. Dell et al. (2012, herein DJO12) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJO12 findings. Burke et al. (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao et al. (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJO12-type results on the same subset of countries as used in DJO12 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greßer et al. (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang et al. (2023) updated the DJO12 data set and applied an estimator robust to mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell et al. (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke et al. (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke et al. (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95% confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans –86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

Barker (2023) criticized the DJO12 assumption that countries can be grouped into fixed “poor” and “rich” categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is taken into account the original temperature effects reported by Dell et al. became small and insignificant.

Berg et al. (2023) argued that countries shouldn’t be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response coefficients then grouped countries with similar response coefficients into small panels. They separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100 even using the extreme RCP8.5 scenario they computed the average global GDP loss would be only 1.9% compared to a scenario with no warming. That is, instead of the economy growing 400% it would grow 398%. The implication of Nordhaus’ earlier analysis is that trying to prevent the warming would lead to far less than 398% growth.

To summarize, economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO₂-induced warming may have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO₂ emissions or find poor countries as likely to benefit from it as rich countries.

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. Figure 11.2, from a 2023 OMB-CEA report, shows the expected decrement in U.S. GDP as a function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as “a few percent impact for a few degrees of warming”. Given that the economy’s annual growth rate is expected to be 1-2 percent, the impact of a warming globe is indeed negligible.

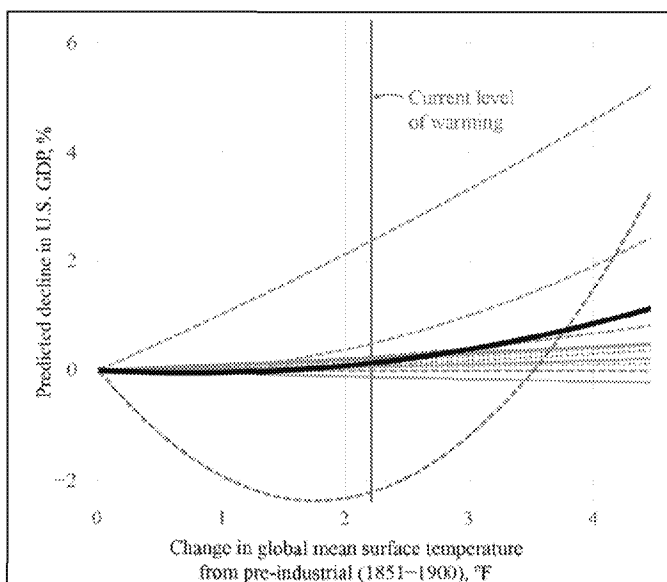


Figure 11.2: Decline in US GDP per degree of warming. Source: XX

11.2 Models of the Social Cost of Carbon

The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO₂, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO₂ entering the atmosphere.

11.2.1 Estimating the SCC

Although the literature refers to “estimates” of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many if not most of the marginal damages or benefits believed to be associated with CO₂ emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO₂ levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known are the Climate Framework for Uncertainty, Negotiation and Distribution (“FUND”, Tol 1997) and Nordaus’ DICE. IAMs embed a “damage function” or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0% GDP penalty at 3°C warming to account for “tipping points” (discrete large-scale environmental changes triggered by crossing a warming threshold) and a “judgmental adjustment” of 0.5% for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as “if-then” statements: *if* the following assumptions hold, *then* the SCC is \$X per tonne. The list of ‘if’ statements includes the premise that the world’s climate and economy work according to the representation in the IAM. One way this may fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), which controls the amount of warming that results from CO₂ emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013) pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013) yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

11.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon, and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO₂ emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.

- **Equilibrium Climate Sensitivity:** IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC’s guidance. Empirically-estimated ECS values tend to be lower than this (see Chapter 9). Dayaratna et al. (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.
- **Damage function coefficients:** IAMs assume CO₂ and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO₂ fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO₂ (see Chapters 2 and 10) the growth effects are likely understated. The DICE model (and others) did not explicitly include any CO₂ fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg et al. 2023) and econometric simulations of agricultural changes (McKittrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.
- **Emission scenarios:** IAMs generate SCC estimates that increase as the pre-existing concentration of CO₂ increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.
- **Abatement costs:** IAMs represent the cost to the economy of reducing CO₂ emissions. If CO₂ emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the US Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore et al. (2017). But as discussed in Chapter 10, McKittrick (2025) showed that Moore et al. (2017) had used a database in which half the CO₂ change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA’s SCC revision attributable to agricultural yield losses was unwarranted.

11.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 10 looked at climate change and US agriculture. Evidence shows that CO₂ fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. In particular Haverd et

al. (2020) found the observed CO₂ fertilization rate has been almost double what had been predicted by crop models. Dayaratna et al. (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO₂ fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only \$18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only \$0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO₂ emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, \$75 per tonne. Deflated by a MCPF value of 1.5 that would result in a carbon tax of \$50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle, 2019). A pre-tax price of \$3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

11.2.4 Tipping points

SCC calculations typically consider gradual impacts of a warming climate, such as slowly-melting glaciers and increasing average temperature. A driver of potentially high values of the Social Cost of Carbon (SCC) is the introduction into models of discrete catastrophic outcomes associated with abrupt changes (Dietz et al., 2021). They are often referred to as “tipping points.”

The term “tipping point” mingles two different physical concepts that pose different research challenges. Many physical systems are inherently stable unless acted upon with sufficient external energy. For example an ice cap might remain intact over a wide range of temperatures but once the temperature crosses the 0°C threshold it melts. Such discontinuities are ubiquitous in nature and require an external force. Whether the force needs to be large relative to the size of the system depends on the underlying stability of the system.

A different type of tipping point is called a *bifurcation* and arises from the study of the internal dynamics of nonlinear systems (Crawford, 1991). Many systems have been observed to have more than one equilibrium point and can move between them with minimal or no external influence. For example a weather system might have two different equilibrium states: one calm and one with a tornado. A transition from one to another can happen either with no external force or with a minuscule change, such as a flap of the proverbial butterfly’s wings (Shen et al. 2014). The term “tipping point” is sometimes used to mean a bifurcation of this type and implies instability inherent in the system itself, which is not necessarily dependent on outside forces. It depends, instead, on parameters of the system taking values that support the emergence of bifurcations (Crawford, 1991).

The two different concepts imply different research questions. Regarding the first we are interested in whether components of the climate system are susceptible to abrupt discontinuities in response to sufficiently-large anthropogenic forcing. Regarding the second we are interested in whether the Earth’s climate system has inherent bifurcations that imply the possibility of abrupt transitions with or without external forcing.

Models have been developed that imply the latter is a possibility. Kypke et al. (2020) presented a simple climate model in which the GHG concentration is one of the parameters that controls the emergence of

bifurcations of the Arctic climate to one with both cold and warm equilibria. If sufficiently high GHG forcing combined with a sufficiently high rate of ocean heat transport are imposed a bifurcation becomes possible. More generally GCMs have been observed to contain bifurcations and multiple equilibria (Brunetti and Ragon, 2023).

The possible existence of bifurcations in the Earth's climate system implies abrupt transitions are possible, not just in response to large forcing but to small perturbations as well. This places tipping points into the category of low-likelihood and potentially catastrophic events, such as large meteor strikes. A key question to ask is whether those kinds of tipping points can be predicted. Current research has not resolved that question (Dakos et al., 2024) and indeed may not be able to since one implication of the “butterfly effect” is the existence of predictability boundaries of nonlinear systems (Palmer et al., 2014). It is therefore not obvious how to incorporate such possibilities into SCC calculations. Small variations in assumptions will lead to arbitrarily large variations in the resulting SCC with no grounds for choosing among them. If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict or prevent it from happening.

The IPCC AR6 (Chapter 1) focuses mainly on the first type of tipping point, namely an abrupt change in response to external forcing. This is also the meaning associated with popular usage of the “tipping point” concept in discussions of climate change (see [[HYPERLINK "https://report-2023.global-tipping-points.org/what-is-a-tipping-point/"](https://report-2023.global-tipping-points.org/what-is-a-tipping-point/)] for example). As summarized by the IPCC AR6, there is evidence of abrupt change in the paleoclimate record, and some of these events have been interpreted as tipping points. Some projections with Earth System Models for example have produced tipping points such as Amazon forest dieback in response to specified values of CO₂ concentration or temperature increases.

The alarm surrounding climate tipping points is reflected by *The Global Tipping Points Report* that was launched at the COP28 on 6 December 2023 (Lenton et al., 2023). It identifies more than 25 parts of the climate system said to constitute tipping points. What gets classified as a climate “tipping point” is a moving target. The most common examples in the literature and assessment reports include: Greenland ice sheet disintegration, West Antarctic ice sheet disintegration, summertime disappearance of Arctic sea ice, Amazon rainforest dieback, coral reef dieoff, thawing of permafrost and methane hydrates, Atlantic Meridional Overturning Circulation collapse, boreal forest shift, West African monsoon shift, and Indian Monsoon shift.

All such tipping points require a certain amount of system instability in order to exhibit an abrupt transition in response to warming. For this reason there seems to be very little to discriminate between a tipping event and natural climate variability. Natural climate variability has in the past produced shifts in the West African and Indian monsoons, Amazon forest and coral reef dieback, and disintegration of the Greenland and West Antarctic ice sheets. These impacts can be reversed on the decadal timescales associated with natural climate variability and ecosystem responses.

Some abrupt changes are potentially more consequential, including collapse of the West Antarctic ice sheet and collapse of the Atlantic Meridional Overturning Circulation (AMOC). The IPCC AR6 WG1 Summary for Policy Makers states:

"The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emission scenarios. While there is high confidence in the 21st century decline, there is only low confidence in the magnitude of the trend. There is medium confidence that there will not be an abrupt collapse before 2100." (C.3.4)

"There is limited evidence for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping

points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios (e.g., SSP5-8.5)." (B.5.2)

For the purpose of SCC calculations the research question implied by this type of tipping point is whether such events have been observed in the past in climate conditions similar to what we currently experience or will in the near future. The IPCC AR6 finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet. It finds there is no tipping point associated with Arctic Sea ice (AR6 Technical Summary p. 76)

Dietz et al. incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25 percent to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However the IPCC considers this scenario *very unlikely* (AR6 Technical Summary p. 107).

In summary, there may be unknown bifurcation tipping points that are associated with natural climate processes, but this possibility does not translate into specific guidance on the SCC. There are potential abrupt change points in the climate system in response to warming, although the IPCC assigns low probabilities to most, including the largest ones. When these have been taken into account the result is only a modest increase in the SCC value in the 21st century.

11.2.5 Are there alternatives?

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung, 2017) stated it's "time to kill it" due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However the uncertainty of SCC estimates doesn't mean that other regulatory measures are inherently better or more efficient. Many emissions regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) cost far more per tonne of abatement than any mainstream SCC estimate which is sufficient for establishing they fail a cost-benefit test.

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12 GLOBAL CLIMATE IMPACTS OF U.S. EMISSIONS POLICIES

Chapter Summary

U.S. policy actions are expected to have undetectably small direct impacts on the global climate and any effects will emerge only with long delays.

12.1 The scale problem

The emissions rates and atmospheric concentrations of criteria air contaminants are closely connected because their lifetimes are short and their concentrations are small; when local emissions are reduced the local pollution concentration drops rapidly, usually within a few days. But the global average CO₂ concentration behaves very differently, since emissions mix globally and the global carbon cycle is vast and slow. Any change in local CO₂ emissions today will have only a very small global effect, and only with a long delay.

Following the emission of a pulse (release) of CO₂ into the atmosphere only about 40 ± 15 percent of the emitted CO₂ will have been sequestered after twenty years. That fraction rises to 75 ± 10 percent after a thousand years, and the remainder will be gradually removed over the ensuing tens of thousands of years (Ciais et al., 2013, pp. 472-473). Consequently, any reduction in U.S. emissions would only modestly slow, but not prevent, the rise of global CO₂ concentration. And even if global emissions were to stop tomorrow, it take decades or centuries to see a meaningful reduction in the global CO₂ concentration and hence human influences on the climate.

Reducing the atmospheric stock of CO₂ would require emissions to fall below the natural sequestration rate, assuming the entire increase is anthropogenic. Since that rate has been averaging about 50% of emissions in recent decades, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO₂. The 1997 Kyoto Protocol proposed to cap industrial nations' CO₂ emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy was too difficult for most nations to implement, full compliance would not have substantially reduced atmospheric CO₂ levels. It would only have slightly slowed CO₂ growth, reaching the projected year 2100 level in 2105 instead (Wigley, 1998). Lomborg (2016) estimated that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, even drastic local actions will have negligible local effects, and only with a long delay. The practice of referring to unilateral US reductions as “combatting climate change” or “taking action on climate” therefore reflects a profound misunderstanding of the scale of the issue.

12.2 Case study: US motor vehicle emissions

The scale problem can be illustrated with reference to U.S. motor vehicles. The EPA's 2009 Endangerment Finding focused on CO₂ emissions from cars and light-duty trucks in the U.S. because Section 202(a) of Clean Air Act mandates the EPA to set emissions standards for motor vehicles if pollutants are found to endanger public health or welfare. The 2009 Endangerment Finding therefore

obligated the EPA to regulate emissions from new motor vehicles, ostensibly to reduce or eliminate climate-related harms to the US public.

Two questions that naturally arise are: (1) How large a reduction in CO₂ emissions would result from such regulation? and (2) What would be the climate impact of such regulation?

The first question can be addressed by comparing US vehicle-based CO₂ emissions to the global total. The second question can be addressed by using the fact that the reduction in global warming would be, according to the models relied upon by the EPA, proportional to the reduction in global emissions, keeping in mind that the change in the CO₂ content of the atmosphere in any given year is the result of total global CO₂ emissions, not just U.S. emissions.

In 2022, the emissions from U.S. cars and light duty trucks totaled 1.05 billion metric tons of carbon dioxide (GtCO₂, EPA 2024). Meanwhile global CO₂ emissions from energy use totaled 34.6 GtCO₂ (Energy Institute 2024). Hence U.S. cars and light trucks account for only 3.0% of global energy-related CO₂ emissions. To a first approximation we can say that even eliminating all US vehicle-based emissions would change the multidecadal warming trend by at most 3%. For the period 1979-2023, which has the most extensive global coverage of a variety of weather data types, warming trends are determined to a precision of about $\pm 15\%$, so the impact of reducing the rate of global warming by eliminating U.S. vehicle CO₂ emissions would be far below the limits of measurability.

Given that global-average temperature is the most direct climate change metric, impacts on any secondary climate metrics (e.g. severe weather, floods, drought, etc.) from reducing U.S. vehicle CO₂ emissions would be even less measurable.

Consequently, in contrast to the case of local air contaminants like particulates and ozone, even the most aggressive regulatory actions on GHG emissions from U.S. vehicles cannot be expected to remediate alleged climate dangers to the US public on any even remotely-measurable scale.

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GLOSSARY

2XCO₂: Doubling of the atmospheric carbon dioxide (CO₂), a commonly used baseline for addressing climate change. In 2025, atmospheric CO₂ concentrations were approximately 50% of the way to 2XCO₂ compared to 1800.

ABATEMENT: In the context of environmental policy, the reduction of emissions.

ACE (Accumulated Cyclone Energy): A statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds.

ACIDIFICATION: A commonly used term for the reduction in ocean pH from more alkaline to less alkaline values.

ACRIM (Active Cavity Radiometer Irradiance Monitor) GAP: the gap in total solar irradiance data between 1989 and 1991 caused by a delay in the launch of a satellite-borne monitor in time to overlap and intercalibrate with the prior system.

AEROSOLS: Tiny solid or liquid particles suspended in the air.

ALKALINE: Having a chemical pH greater than 7.0. The “opposite” of acidic, which means a pH less than 7.0.

AMBIENT: Relating to the immediate surroundings of something.

ANTHROPOGENIC: Created by humans.

AR (Assessment Reports): Periodic assessments published by the Intergovernmental Panel on Climate Change evaluating current knowledge of the climate system, global change, and associated issues. An AR now consists of reports from three working groups, the first (WG1) concerned with physical science and the others concerned with societal impacts and mitigation strategies. The most recent was the AR6.

ATTRIBUTION: Assertion of a causal relation, chiefly from anthropogenic GHG emissions to observed climate patterns.

AUTOCORRELATION: The phenomenon in which the current value of a random time series variable is correlated with its value in a previous time period.

BIOMASS: The total quantity or weight of organic matter in a given area or volume.

CARBON: The 6th element in the periodic table. Popularly used as a shorthand term for carbon dioxide.

CMIP (Coupled Model Intercomparison Project): The Intergovernmental Panel on Climate Change's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s). The two most recent were the CMIP5 and CMIP6 for, respectively, AR5 and AR6.

CONUS: The contiguous 48 U.S. states.

DICE (Dynamic Integrated model of the Climate and Economy): An Integrated Assessment Model developed by William Nordhaus in 1993.

DISCOUNT RATE: The interest rate used to convert future costs and benefits into their present value. Varies inversely with present value so a high discount rate reduces the present value of future costs and benefits.

DRY ICE: Frozen carbon dioxide.

ECONOMETRICS: The branch of economics concerned with the use of statistical methods (chiefly multiple regression) to analyse economic systems.

ECS (Equilibrium Climate Sensitivity): The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO₂ concentration compared to pre-Industrial levels.

EL NIÑO: The warm phase of the El Niño – Southern Oscillation, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

EMISSIONS SCENARIO: An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO₂ uptake by land and ocean.

ENDANGERMENT FINDING (EF): The 2009 finding by the Administrator of the Environmental Protection Agency that emissions of well-mixed greenhouse gases (primarily CO₂) endanger human health and welfare.

ENSO: El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean.

FACE: (Free-Air CO₂ Enrichment) Large-scale open-air studies that expose plants to elevated CO₂ levels, simulating future climate scenarios.

FOSSIL FUEL: A natural hydrocarbon fuel such as coal, oil, or natural gas formed in the geological past from the remains of living organisms.

FUND (Framework for Uncertainty, Negotiation, and Distribution): An Integrated Assessment Model developed by Richard Tol in 1997.

GBR (Great Barrier Reef): The world's largest coral reef ecosystem located off the northeast coast of Australia.

GDP (Gross Domestic Product): Total market value of all the final goods and services produced within a country's border, usually over one year.

GHCN (Global Historical Climatology Network): A time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

GLOBAL GREENING: The satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s.

GNP (Gross National Product): Total market value of all the final goods and services produced by the citizens of a country, including exports and imports, usually over one year.

GDP (Gross National Product): Total market value of all the domestically-produced final goods and services produced by the citizens of a country, usually over one year.

GREENHOUSE EFFECT (GHE): The tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.

GREENHOUSE GAS (GHG): An atmospheric gas that absorbs and emits infrared radiation, especially water vapor, CO₂, and methane.

HURST PHENOMENON: See long term persistence.

HYDROLOGY: The study of the movement of water, especially on land and in the atmosphere.

IAM (Integrated Assessment Model): A computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions.

IEA (International Energy Agency): A Paris-based intergovernmental organization, established in 1974, that provides policy recommendations, analysis and data on the global energy sector.

IPCC (Intergovernmental Panel on Climate Change): A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies.

IR (Infrared): Heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

LA NIÑA: The cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON): A form of autocorrelation in which random fluctuations induce long term but not permanent changes in the mean value of a series, which shows up in some climate data series as cyclical or trending patterns on short time scales.

MAIZE: Corn.

MODEL: A computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes.

MORTALITY: Death or number of deaths, usually expressed for a specific population and period.

NCA (National Climate Assessment): A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States. There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023).

OECD (Organization for Economic Cooperation and Development): A group of 38 member countries that have a democratic system of government and free economic systems.

PALEOCLIMATE: Climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of “proxy” measurements such as tree rings, ice core, pollen records, etc.

PDI (Power Dissipation Index): A statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds.

PHOTOSYNTHESIS: The process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function).

PPM: Parts per million, a measure of the concentration of a substance in (for example) the atmosphere

PRE-INDUSTRIAL: The near-term historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s.

RADIATIVE FEEDBACK: A change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature.

RADIATIVE FORCING: The change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

RCP (Representative Concentration Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC’s Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they

assume in 2100 relative to pre-Industrial times, in Watts per square meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

REGRESSION: A statistical method for selecting the coefficients of a linear equation to explain the behaviour of a dependent variable in terms of variations in one or more explanatory variables.

RICARDIAN ANALYSIS: A method used in environmental economics named after David Ricardo to estimate the economic impacts of climate change, particularly on agriculture, by making use of the hypothesis that expected changes in the return to future agricultural activity will be capitalized into current land values.

SCC (Social Cost of Carbon): An estimate of the net economic damages, measured in present-value dollars, caused by emitting one additional ton of CO₂ into the atmosphere.

SSP (Shared Socioeconomic Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

TC: Tropical cyclone.

TMAX: The daily maximum surface air temperature.

TMIN: The daily minimum surface air temperature.

TOA: Top of atmosphere.

TOXICOLOGY: The study of the adverse effects of chemical substances on living organisms.

TREND: A coefficient, usually estimated using linear regression, representing the slope of a line of best fit through a time series of data, indicating any tendency for the series mean to move up or down over time.

TSI (Total Solar Irradiance): The measure of the total amount of incident solar radiation per unit area, including all wavelengths of electromagnetic radiation, that reaches the Earth's atmosphere. Typically shown in units of watts per square meter (W/m²).

UHI (Urban Heat Island): The tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

USHCN: The U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations.

ABOUT THE AUTHORS

John Christy, Ph.D. is the Distinguished Professor of Atmospheric and Earth Sciences and Alabama's State Climatologist at the University of Alabama in Huntsville. He has a B.A. (Mathematics) from CSU Fresno and an M.S. and Ph.D. (Atmospheric Sciences) from the University of Illinois in Urbana-Champaign. He is a Fellow of the American Meteorological Society and recipient of The NASA Medal for Exceptional Scientific Achievement for constructing, with Dr. Roy Spencer, the first global atmospheric temperature dataset from polar orbiting satellites. He served as Lead Author of the 3rd IPCC Assessment Report (2001), he has coauthored National Academy of Science expert reports on Climate Observations (1995) and Surface Temperature Reconstructions (2006), and he has served on the NOAA Climate Change Science Program, NASA's Earth Science Subcommittee, the National Research Council Space Studies Board and the EPA Science Advisory Board. In addition, Dr. Christy has given testimony in 20 Congressional Hearings.

Judith Curry, Ph.D. is Professor Emerita at the Georgia Institute of Technology, where she served as Chair of Earth and Atmospheric Sciences for 13 years. She is President and co-founder of Climate Forecast Applications Network (CFAN). Curry has a PhD in Geophysical Sciences from the University of Chicago. She has authored or coauthored 192 peer-reviewed papers in atmospheric and climate sciences, two textbooks, and most recently the book *Climate Uncertainty and Risk*. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, American Geophysical Union, and a Member of the American Academy of Sciences and Letters.

The Honorable Steven E. Koonin, Ph.D. is the Edward Teller Senior Fellow at Stanford's Hoover Institution. He has served as Under Secretary for Science at the Department of Energy (2009-2011), as Chief Scientist for BP (2004-2009), and as a professor at Caltech (1975 – 2004, the last nine years as Vice President and Provost). Koonin is a member of the National Academy of Sciences and the JASON group of government advisors, as well as a Governor of Lawrence Livermore National Laboratory, having served in similar capacities for the Los Alamos, Sandia, Brookhaven, and Argonne National Laboratories. Other prior roles include a University Professor at NYU, a non-resident Senior Fellow at AEI, and a Trustee of IDA.

Koonin has a BS in Physics from Caltech and a PhD in Theoretical Physics from MIT. He authored the 2021 bestseller *Unsettled: What Climate Science Tells Us, What It Doesn't, and Why It Matters*, the 1985 textbook *Computational Physics*, and some 200 peer-reviewed papers in physics and astrophysics, scientific computation, energy technology and policy, and climate science.

Ross McKittrick, Ph.D., is a Professor of Environmental Economics at the University of Guelph in Ontario, Canada. He holds a BA in economics from Queen's University, and an MA and Ph.D. in economics from the University of British Columbia. He has published widely in both economics and physical science journals on topics related to climate change, pollution and public policy. His book *Economic Analysis of Environmental Policy* was published by the University of Toronto Press in 2010. His background in applied statistics has led him to author or coauthor peer-reviewed publications across a wide range of topics in the physical sciences including paleoclimate reconstruction, malaria transmission, surface temperature measurement, climate attribution methodology and climate model evaluation. Professor McKittrick has made many invited academic presentations around the world, and has testified before the US Congress and committees of the Canadian House of Commons and Senate.

Roy W. Spencer, Ph.D., is a Principal Research Scientist at the University of Alabama in Huntsville. He holds a BS in Atmospheric and Oceanic Science from the University of Michigan, and MS and PhD in Meteorology from the University of Wisconsin -Madison. Spencer's published research has focused on monitoring of weather processes and climate change from Earth-orbiting satellites, as well as using simple physical models for diagnosing climate sensitivity and climate feedbacks. As a NASA Senior Scientist for Climate Studies he served as the U.S. Science Team Leader for the Advanced Microwave Scanning Radiometer (AMSR-E) flying on the Aqua satellite, providing our most accurate global measurements of sea surface temperatures, sea ice, and several other features of the climate system. Along with Dr. John Christy, Spencer developed the first satellite-based technique for global temperature monitoring, for which they received NASA's Exceptional Scientific Achievement Medal and the American Meteorological Society's Special Award.

Review of the Fifth National Climate Assessment

[TOC \O "1-3" \H \Z \U]

1 INTRODUCTION

1.1 About this Report

This report responds to a request from OSTP Director Michael Kratsios (reproduced in Appendix XX) that we assess the suitability of the Fifth National Climate Assessment for informing climate and energy policies.

To conduct this assessment we reviewed NCA5 itself, NASEM review of the Third Order Draft and the USGCRP responses to the review. We have drawn upon our long experience working on advisory reports, including for the NASEM, IPCC and other organizations, as writers, reviewers and project leaders.

We find that NCA5 should not be relied on for policy making as it is an incomplete and misleading picture of our understanding of the changing climate and the risks it poses to the nation. NCA5 was selective and incomplete in its survey of the science as of its publication date in 2023 and has become even more so in the years since. We have reviewed many key scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025, herein denoted "CWG25"). The overall effect of its biases and omissions is an excessively dire picture of climate risk.

Our report begins with background on the National Climate Assessments. We then discuss the standards by which we have assessed NCA5, followed by specific deficiencies that we have ~~we've~~ identified.

1.2 About the National Climate Assessments

The U.S. Global Change Research Program (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The National Climate Assessment (NCA) Reports evolved from the GCRA requirement to

Prepare and submit to the President and the Congress an assessment which (1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

The five NCA Reports to date have interpreted this mandate in different ways:

- NCA1 (2000) was a multidisciplinary effort to study and portray in regional detail the potential effects of human-induced global warming on the United States.
- NCA2 (2009) was a relatively short report that not only focused on the potential consequences of climate change, but also sought to identify potential adaptation measures and identify the highest priorities for future research.

- NCA3 (2014) was an expanded effort that continued along the lines of NCA2, and was distinguished by a comprehensive review process, including a review by the National Academy of Sciences.
- NCA4 (2017/2018) was an expanded effort published in two volumes: I Climate Science Special Report, and II Impacts, Risk, and Adaptation in the United States. This was the first NCA report to devote significant effort to assessing climate science. NCA4 introduced a traceability analysis for each key finding, including a cursory description of uncertainties.
- NCA5 (2023) returned to a single volume format, reducing discussion of climate science to a cursory two chapters, with continuing with a focus on regional and sectoral impacts of climate change. NCA5 expanded its remit to topics that are arguably outside the purview of the USGCRP, focusing on "Climate Action" and policy recommendations with a social justice emphasis. NCA5's self-description is reproduced as Appendix II.

These successive interpretations of the NCA are poorly aligned with the GCRA's statutory requirements. Only NCA4 gives serious consideration to climate science, which receives the great majority of USGCRP funding, and even then misrepresents some important points (see the Box nearby for an example). Natural climate variability is essentially dismissed as unimportant in NCA4 and barely mentioned in NCA5 in most contexts, despite the mandate to include both human-caused and natural climate change. Most significantly, NCA5 has redirected the focus away from climate science and even the hazard elements of impacts, towards evaluation of societal vulnerabilities and advocacy for particular policy options, especially wind and solar power. The cover image for the NCA5 Report is the installation of a solar panel.

START BOX

NCA4's Figure ES.5: A Tale of Deception and Review Failure

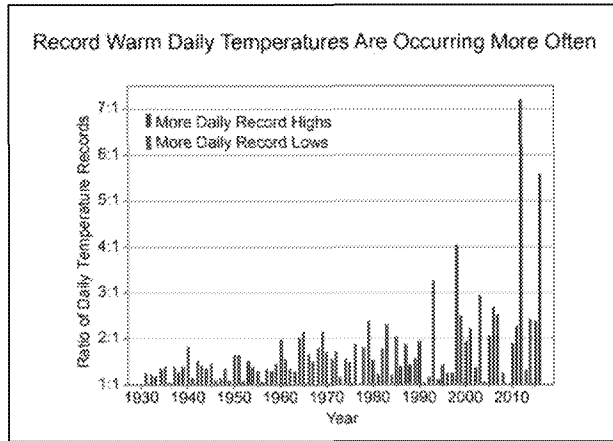
A disappointing example of NCA4's misrepresentation of climate science involves U.S. temperature extremes. Here is a summary of the issue; details can be found in [Koonin \(2024\)](#).

Commented [A1]: Cite Unsettled, 2nd edition

NCA4's Part I (Climate Science Special Report, CSSR) says (prominently and with *Very High Confidence*) on Page 19 of the Executive Summary:

There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records.

and offers this figure in support:



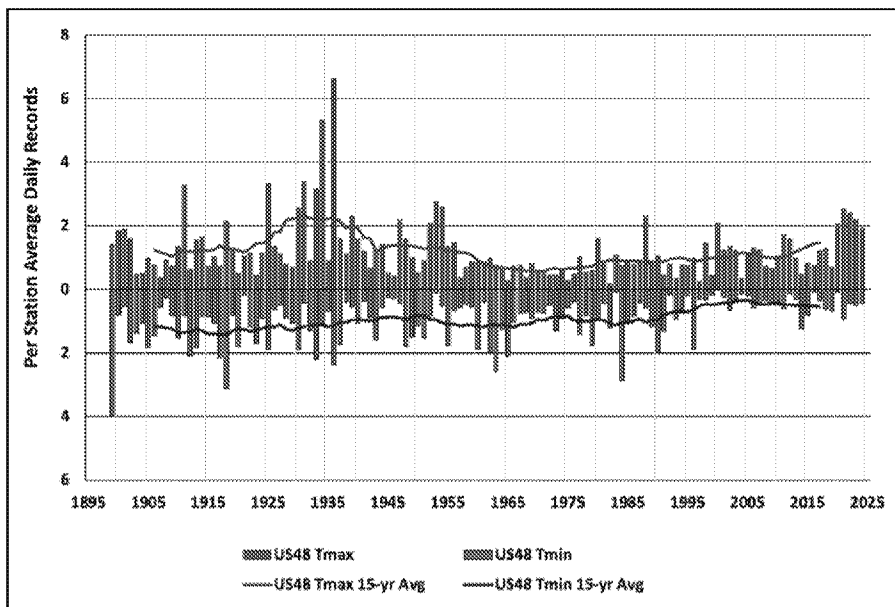
CSSR Figure ES.5 The ratio of the number of daily record high temperatures to daily record low temperatures for many stations across the 48 contiguous states is shown for each year from 1930 to 2017. The lighter bars show a year in which there were more record highs than lows, while the darker bars show years in which there were more record lows than highs. The height of the bar indicates the ratio of record highs to record lows for each year. For example, a ratio of 2:1 for a dark bar means that the stations had twice as many record daily lows as record daily highs for that year. (CSSR, 2017)

Commented [A2]: Cite CSSR

Three idiosyncratic choices combine to generate the figure's seemingly alarming rise in recent decades. First, because the record extremes tallied are defined conventionally (i.e., each more extreme than any preceding value in the history), the numbers of record highs and record lows are both expected to decline through the years (it becomes increasingly unlikely that a record will be exceeded). Second, the graph displays not the numbers of record highs and lows, but rather their ratio. And finally, the history begins only in 1930 when, in fact, data exist beginning in the late 19th Century. The upshot of these choices is that the resultant figure is guaranteed to show a long period of quiescence around followed by dramatic variations, creating the impression of large changes in recent decades, even if they aren't present.

Figure 6.3.3 of our report (reproduced below) shows the results of a proper analysis – defining each record as the singular extreme in the history, displaying numbers of warm and cold records separately, and beginning the analysis in 1899 rather than 1930. It makes evident the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. The increased heat of the past five years is too brief to be deemed climatically significant and, in any event, occurred after the CSSR was published in 2017. On the cold side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by CONUS, with 1917 in 2nd place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13 percent of the extreme cold events were measured. In contrast, 25 percent of the extreme Tmax records were achieved in the last quarter, in accordance with statistical expectations. As a result, the ratio shown in the CSSR explodes in recent decades. And the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate *less* prone to extremes, in sharp contrast to the title of the CSSR figure, "Record Warm Daily Temperatures Are Occurring More Often".

Commented [A3]: What do we call it?



Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92 percent of observations in the 126-year period since Dec 1898. US48: contiguous U.S. states. Tmax: maximum temperature. Tmin: [minimum temperature]

Commented [A4]: Cite our report

The National Academies' expert review panel [[HYPERLINK "https://www.nap.edu/catalog/24712/review-of-the-draft-climate-science-special-report"](https://www.nap.edu/catalog/24712/review-of-the-draft-climate-science-special-report)] the discussion of temperature extremes in a [[HYPERLINK "https://biotech.law.lsu.edu/blog/Draft-of-the-Climate-Science-Special-Report.pdf"](https://biotech.law.lsu.edu/blog/Draft-of-the-Climate-Science-Special-Report.pdf)] of the CSSR. In reference to the CSSR's Key Finding 2 of Chapter 6, they said:

Further, it is difficult to understand how a statement that includes increases in extreme warmth can be associated with a high confidence or extremely likely statement, given that most of the graphics in this chapter show a decrease in extreme warmth in the historical record.

The Federal official in charge of the CSSR (Michael Kuperberg, Executive Director of the USGCRP) [[HYPERLINK "https://science2017.globalchange.gov/PDFs/CSSR-NASresponse_110217.pdf"](https://science2017.globalchange.gov/PDFs/CSSR-NASresponse_110217.pdf)] to the Academies' review by noting that

Almost every recommendation from the NAS was incorporated [in the final version]... and a new figure was added on changes in record high and low temperatures

The “new figure” referred to is the Figure ES.5, which did not appear in the draft reviewed by the Academies’ panel. It seems unlikely that the Academies panel ever saw that figure because they surely would have commented if they had and it wouldn’t have survived to publication. And the figure’s problems were evidently not flagged (or were ignored) in the subsequent internal government reviews.

While the following statement has far less headline potential than that from the CSSR’s page 19 quoted at the beginning of this box, it has advantage of being correct:

There have been some changes in temperature extremes across the contiguous United States. The annual number of high temperature records set shows no significant trend over the past century [or over the past 40 years] but the annual number of record cold nights has declined by a factor of 4 since 1895, somewhat more rapidly in the past 30 years.

Commented [A5]: Check this statement

Commented [A6R5]: R² is 0.02, so not significant for 1978-2017.

END BOX

1.3 Standards for Assessing NCA Products

Good climate and energy policies will balance the risks and benefits of a changing climate against the world’s growing demand for reliable and affordable energy. To strike that balance, policymakers must understand at least two complex and nuanced topics –the certainties and uncertainties of climate science and the technoeconomic realities of energy systems. Experts in those subjects are the only people who can bring the facts to the discussion and so have a unique responsibility to communicate their understanding to non-experts clearly, completely, and without bias.

Expertise in energy systems resides largely in the private sector, where it is essential to providing the reliable and affordable energy services that are the lifeblood of society. Understanding is therefore continually refined and tested by the discipline of the marketplace. In contrast, climate science expertise is found largely in the non-profit realm of universities and government laboratories and so has a more academic character.

Because climate is at the core of human existence, it can engender passion and emotion. Indeed, some younger climate scientists have gone into the field to “save the planet.” So it isn’t surprising that objectivity can suffer when climate scientists communicate their understanding to non-experts. Further, the field of climate science has been politicized by NetZero mandates. When that happens, it This lack of objectivity usurps the public’s right to make informed choices and undermines their confidence in the scientific enterprise.

Philip Handler, President of the National Academy of Sciences, identified the problem in a 1980 [HYPERLINK "<https://science.sciencemag.org/content/208/4448/1093>"] that resonates eerily four decades later:

Difficulty arises in the scientific community from confusion of the role of scientist *qua* scientist with that of scientist as citizen, confusion of the ethical code of the scientist with the obligation of the citizen, blurring the distinction between intrinsically

scientific and intrinsically political questions. When scientists fail to recognize these boundaries, their own ideological beliefs, usually unspoken, easily becloud seemingly scientific debate.

In Appendix XX we include a letter of guidance from the Office of General Counsel, U.S. Department of Energy, summarizing the extent of statutory requirements governing USGCRP work products in general and NCA products in particular.

We can summarize the standards applicable to the NCA as follows:
- details.

Beyond the statutory requirements we draw attention to two other pertinent standards. President Trump's executive order of May 23, 2025, "[[HYPERLINK "https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/"](https://www.whitehouse.gov/presidential-actions/2025/05/restoring-gold-standard-science/)]" enumerates some of the characteristics of good science:

- i. reproducible;
- ii. transparent;
- iii. communicative of error and uncertainty;
- iv. collaborative and interdisciplinary;
- v. skeptical of its findings and assumptions;
- vi. structured for falsifiability of hypotheses;
- vii. subject to unbiased peer review;
- viii. accepting of negative results as positive outcomes; and
- ix. without conflicts of interest.

Although these should be self-evident to those trained in science, it is surprising that some have found them [[HYPERLINK "https://www.theguardian.com/commentisfree/2025/may/29/trump-american-science"](https://www.theguardian.com/commentisfree/2025/may/29/trump-american-science)].

Finally we consider that when scientific reports are being assembled that will be highly influential on climate policymaking there are other desiderata, including statements about the strength of climate knowledge. The IPCC's approach is based on judgment of the available evidence and agreement among experts. More sophisticated knowledge characterizations for risk management include: [REFERENCE AVEN](#)

- The degree to which the assumptions made are reasonable/realistic based on background knowledge—concern about the focus on implausible emissions scenarios RCP8.5/SSP5–8.5
- The degree to which data/information exists and are reliable and relevant—the historical and paleo database is inadequate for a complete characterization of natural climate variability on multi-decadal to millennial time scales
- The degree to which there is disagreement among experts (including those from different environments or academic fields)—attempts to suppress disagreement and alternative perspectives among experts
- The degree to which the phenomena involved are understood and accurate models exist—concerns about the fidelity and utility of climate models
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns and—neglect of the unknown knowns associated with natural climate variability

Commented [A7]: Terje Aven, "Improving Risk Characterisations in Practical Situations by Highlighting Knowledge Aspects, with Applications to Risk Matrices," Reliability Engineering & System Safety 167 (November 2017): 42–48

[[HYPERLINK "https://www.sciencedirect.com/science/article/pii/S0951832016306950"](https://www.sciencedirect.com/science/article/pii/S0951832016306950)]

With this background we now present our critique of NCA5.

2 OVERVIEW CHAPTER: HYPERBOLIC ADVOCACY LANGUAGE AND NON-SCIENTIFIC TONE

The opening Chapter 1 “Overview” holds a prominent place since it serves as a summary of the whole report and is all that many will read. While there is much sound scholarly content in the later sections of NCA5, Chapter 1 is marred by pervasive use of advocacy language and a tone overly focused on promoting aggressive emission reduction policies. The authors must have known this chapter would be mined for quotes by the media and activists looking to add an imprimatur of scientific authority to oversimplified declarations of opinion. Many examples can be cited; here we provide a few particularly egregious ones.

The chapter opens as follows:

The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases.

This statement presupposes all warming is anthropogenic in origin, all warming is bad and causes economic damage, warming causes extreme weather to intensify. Such sweeping generalizations go well beyond what science has or can establish. A scientifically-sound version of this paragraph would instead say something like the following:

The Earth is undergoing a warming trend caused by a combination of natural and anthropogenic influences. This warming can be expected to generate a mix of benefits and harms that varies by region, to which society should be prepared to adapt. There is evidence that some types of extreme weather have worsened, while others have not changed or have even declined in intensity. Reducing emissions of greenhouse gases can slow the warming process although such policies have proven to be very expensive, so the costs need to be weighed against the potential benefits.

On the next page the Overview goes on to say:

Each additional increment of warming leads to greater risks [here it lists 7 key components of society including food security and the economy]... Without deeper cuts in global net emissions, climate risks to the US will continue to grow... Action to limit future warming and reduce risks can have near-term benefits and opportunities: low-carbon energy jobs, Improved air quality, Health benefits, Economic benefits...”

The authors write as if climate policy does not involve trade-offs and all measures to reduce future warming will be effective and beneficial. But the vast body of scholarship on climate science and economics does not support such simplistic claims. Not every additional increment of warming leads to economic harms, indeed (as is acknowledged in Chapter 19 on Economics) in some cases it is

expected to yield benefits. Nor is climate policy guaranteed to create jobs or benefit the economy; in many cases it has done the opposite. It is a disservice to policymakers not to be honest about this.

Page 9 promotes renewable energy options by arguing that the “levelized” costs of wind and solar power generation have fallen sharply since 2010. But “levelized” refers to the lifetime project cost averaged over all power production and ignores the intermittency problem: namely solar and wind are not always available. It results in an invalid comparison since even if, for instance, the levelized cost of solar energy per megawatt-hour falls below that of coal, coal power is available continuously and on demand whereas solar is not. The proper comparison would adjust for the difference in availability by considering the cost of supplementing solar and wind with backup natural gas-fired systems or battery storage, and on that basis renewable energy remains prohibitively expensive. Here again it is a disservice to readers not to acknowledge these facts.

Page 14 presents future emission scenarios with the following description: “Climate modeling experts develop global climate projections for a range of plausible futures.” The word “plausible” is applied to all the scenarios. The accompanying Figure includes both SSP3-7.0 and SSP5-8.5, the latter reaching the same radiative forcing as RCP8.5. The figure does not contrast observed emissions against model projections nor does it caution readers that SSP3-7.0 and SSP5-8.5 are extreme worst case scenarios that, like RCP8.5, have been heavily criticized in the scientific literature (CWG25 3.2.1). By describing the entire envelope of emission projections as “plausible” the report opens the door to later presenting impacts associated with extreme and implausible emission scenarios as part of a baseline “business-as-usual” future.

Page 17 (and elsewhere) invokes the NOAA Billion Dollar Dataset as an indicator of weather getting worse. Scientists have shown that this is an invalid metric (CWG 10.2) since it measures the growth of the economy not the frequency of extreme weather, and indeed NOAA has withdrawn the data product. Even though it was still distributed by NOAA at the time of the NCA5, the report authors should have assessed it skeptically and seen that it was unfit for the purpose of measuring climate trends.

Page 23 states, in large font:

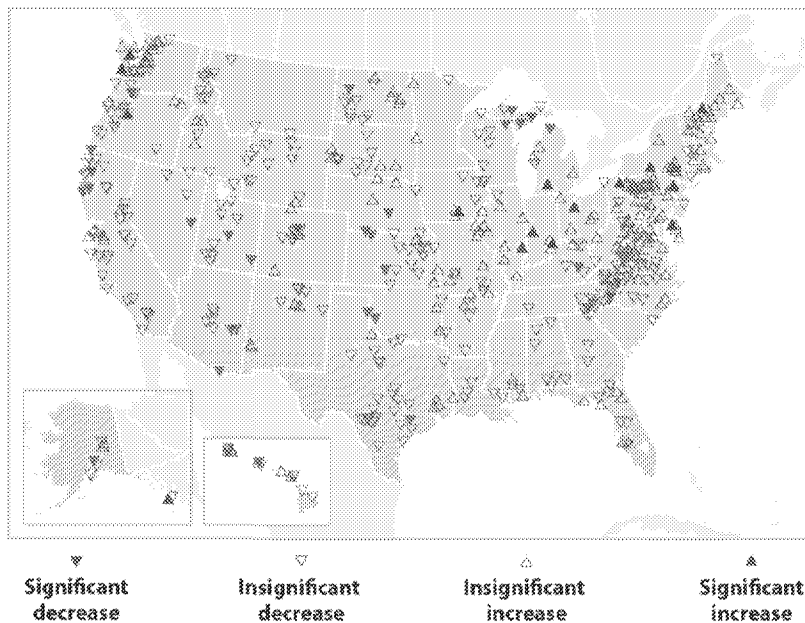
Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities.

It is pointless to try to evaluate this statement on scholarly grounds; it is self-evidently hyperbolic. This kind of language doesn't belong in a scientific assessment report. Its prominent inclusion points not only to the willingness of NCA5 authors to promote hysteria, but also the ineffectiveness of the review process at not ensuring such statements are removed.

We won't try to cite all the remaining examples of advocacy and hyperbole in the Overview chapter; one more example will suffice. Page 26 states “Increasing flooding puts more people and assets at risk.” The accompanying figure contrasts model-projected flood losses by county in 2050 to that observed in 2020 as estimated in Wing *et al.* (2022)¹. Hence the evidence for the claim is not currently-observed trends, it is a model-generated projection of changes. But current trends in U.S.-

¹ Wing, Oliver, William Lehman, Paul Bates *et al.* (2022) Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change* 12 156—162 [HYPERLINK "<https://www.nature.com/articles/s41558-021-01265-6>"]

based flooding reveal a more complex picture with a general overall trend towards less flooding. The Environmental Protection Agency's "Climate Change Indicators: River Flooding" webpage² shows maps both of flood magnitude and frequency. Both show more regions experiencing declines over 1965-2015 than increases. Hence current trends indicate generally declining U.S. flood risks, but the NCA5 Overview not only fails to mention this but declares the opposite based on a single study presenting model-generated forecasts of flood activity decades in the future.



U.S. Flood magnitude trends 1965-2015.

Source: [[HYPERLINK "https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding"](https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding)]

² [[HYPERLINK "https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding"](https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding)]

3 ONE-SIDED OVERSIMPLIFICATIONS IN SCIENCE SUMMARY CHAPTERS

Chapters 2 (Climate Trends) and 3 (Earth Systems Processes) form the scientific core of NCA5. As we will show in the following examples they fail to meet statutory requirements to discuss scientific uncertainties and the role of natural variability, and they fail to meet the more stringent implicit standards expected of a policymaking report.

3.1 Increased Lower Bound of Climate Sensitivity

The promotional tone of Chapter 1 is carried forward into Chapter 3 (Earth System Processes) where, on page 3-10, Key Message 3.2 states “The Estimated Range of Climate Sensitivity Has Narrowed by 50%”. Referring to Equilibrium Climate Sensitivity (ECS) the section elaborates:

Recent improvements in the understanding of how climate feedbacks vary across timescales have narrowed the estimated *likely* range of warming expected from a doubling of atmospheric carbon dioxide by 50% to between 4.5°F and 7.2°F (*high confidence*).... This uncertainty reduction results from advances in combining observations and targeted modeling results from nearly independent lines of evidence, each of which generally agrees on the values of ECS. The lines of evidence include 1) observed present-day variations on monthly to interannual timescales from which cloud and other climate feedbacks are inferred; 2) observed temperature changes between the preindustrial period and present and associated relationships to ERF; and 3) estimated temperature and radiative forcing changes for multiple warm and cold periods in paleoclimate records.

The graphic summary on page 3-11 states

The reduced uncertainty in climate sensitivity and climate feedback has been achieved through unprecedented quantitative synthesis of evidence from observed changes over recent decades, the industrial era, and paleoclimate.

This is a very inadequate description of the situation. The key development in AR6 was a *reduction* of confidence in the ability of climate models to identify ECS and the shift away from the model-based method the IPCC had relied on since AR1 in 1990. The IPCC instead turned to data-driven ECS estimation and specifically chose a single paper from the scientific literature, Sherwood *et al.* (2020³) for the purpose. It combined paleoclimate data, modern instrumental data and modern observations of climate processes, mainly cloud-related, that govern key feedbacks. Sherwood *et al.* used a subjective Bayesian method to determine the likely range of ECS values. The Bayesian approach begins with the researcher specifying a “prior”, namely an expectation of what the answer will be before seeing the data. In this case the prior consists of an expected ECS range based on the researchers’ subjective beliefs. Then the data are allowed to influence the ECS distribution and the final result is a weighted average of the assumed prior and the data-driven result. Sherwood *et al.* found a best (or median) ECS estimate of 5°F (3°C), which was close to previous model-based

³ Sherwood, S. C., Bony, S., Boucher, O., Bretherton, C. S., Forster, P. M., Gregory, J. M., & Stevens, B. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, 58(4). [HYPERLINK "<https://doi.org/10.1029/2019rg000678>"]

estimates but raised the likely lower bound by 1.7°F from 2.5°F to 4.2°F. The IPCC accepted this result and increased the best estimate to 3.1°C.

The NCA5 was published in November 2023. Well before that, in September 2022, Lewis (2023) had been published online at *Climate Dynamics* presenting a forceful critique of Sherwood *et al.*⁴ One of Lewis' points was that Sherwood *et al.*'s result was dependent on their chosen subjective prior. Lewis recommended using an objective Bayesian method, which places primary weight on the data rather than the researcher's expectation. Using that and updated forcing data from AR6, Lewis estimated an ECS best estimate of 3.7°F (2.2°C) with a likely lower bound of 2.7°F (1.6°C).

Hence, in contrast to the promotional language of Chapter 3 a more valid summary of the ECS literature as it stood at the time of writing the NCA5 would be what we wrote in CWG25 (emphasis added):

For the AR6, the IPCC placed primary weight on the results of Sherwood *et al.* (2020) that combined historical and paleoclimate proxies with the process-based approach and yielded a best estimate of 3.1°C with a *likely* range of 2.6–3.9°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood *et al.* analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent *likely* range, and 1.6–3.2°C in the 5–95 percent *very likely* range). **The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent.** The most recent publications on the debate between Sherwood *et al.* and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

3.2 Presenting New Emission Scenarios as a Scientific “Advance”

Chapter 3 pp. 13-14 treats the release of new emission scenarios as a scientific “advance” without addressing the failure of many previous scenarios to match reality or providing an honest assessment of the likelihood that the new ones are biased in the same way.

Key Message 3.3 states “New Data and Analysis Methods Have Advanced Climate Science” and includes the following:

New scenarios of socioeconomic development, and their associated emissions and land-use changes, drive updated climate projections from Earth system models. The Scenario Model Intercomparison Project (ScenarioMIP) organized the main set of 21st-century projection experiments under the latest phase of the Coupled Model Intercomparison Project, CMIP6. These CMIP6 projections used newly developed scenarios based on Shared Socioeconomic Pathways (SSPs; Figure 3.4). Five SSPs represent alternative plausible trajectories of 21st-century GDP and population growth and the pace and pervasiveness of socioeconomic and technological progress within individual nations and across the world (see Table 3 in the Guide to the Report). SSP-specific drivers are used in integrated assessment models (IAMs)

⁴ Lewis, N. (2023). Objectively combining climate sensitivity evidence. *Climate Dynamics*, 61(9–10), 3155–3163. [HYPERLINK "<https://doi.org/10.1007/s00382-022-06398-8>"]. The final citation for this paper is Lewis (2023) because the print edition did not appear until 2023, but the article was accepted in August 2022 and the online edition appeared and was in circulation in September 2022.

to simulate the corresponding evolution of the energy system and the resulting greenhouse gas trajectories. These are in turn used by ESMs to drive their 21st-century projections.

There is nothing wrong with NCA5 discussing the development of new emission scenarios which serve as inputs to climate change projections and impact studies. But it is a serious omission not to inform the reader of the failure of many previous IPCC scenarios to match reality and the tendency of the scenario groups to exaggerate near-term and long-term CO₂ concentration growth (CWG25 3.2.1). It is also a serious omission not to caution readers that many climate impact studies use RCP8.5 which by the time of NCA5 had already been heavily criticized in the literature.

The same section also reports the availability of new and larger model ensembles as a scientific advance, without addressing ways in which models are getting worse in some key respects (CWG Ch 5).

3.3 Uncritical Promotion of “Emergent Constraints”

Chapter 3 page 17 presents the topic of “emergent constraints” in uncritical terms:

An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as “emergent constraints.” The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship.

Emergent constraints appeared in the climate modeling literature as a way to tie GCM behavior to climate observations in hopes of generating insight into real-world ECS. Climate models exhibit a wide range of sensitivities. The idea of emergent constraints is to examine whether the models with shared sensitivity values also share a common representation of some climate process (usually related to clouds) that might indirectly influence ECS. Suppose, for instance, that in low-ECS models the total cloud fraction in the tropics is strongly correlated with that in the southern midlatitudes but in high-ECS models the correlation is weak. Then researchers could check if the observed correlation is strong or weak and draw a conclusion about which type of model, and therefore which ECS value, is more likely.

A problem in the emergent constraint literature is that there has been a large proliferation of proposed correlations with little physical motivation. Many emergent constraints patterned on CMIP5 models failed to work on CMIP6 models (Schlund *et al.* 2020)⁵. In other words, the observed correlations in CMIP5 models between ECS and cloud processes failed to show up in CMIP6 models, indicating that they were likely spurious rather than clues to physical processes governing the Earth climate system. The result was that emergent constraints estimated on CMIP5 models widened the range of estimated ECS values when applied to CMIP6 models.

Schlund *et al.* summarized the problem as follows:

In this study, we systematically analyze 11 published emergent constraints on ECS that have mostly been derived from models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) project... The focus of the study is on testing if these emergent

⁵ Schlund, Manuel, Axel Lauer, Pierre Gentile, Steven C. Sherwood, and Veronika Eyring (2020) Emergent constraints on equilibrium climate sensitivity in CMIP5: do they hold for CMIP6? *Earth System Dynamics* 11 1233-1258 [[HYPERLINK "https://doi.org/10.5194/esd-11-1233-2020"](https://doi.org/10.5194/esd-11-1233-2020)]

constraints hold for [Earth System Models] participating in the new Phase 6 (CMIP6). Since none of the emergent constraints considered here have been derived using the CMIP6 ensemble, CMIP6 can be used for cross-checking of the emergent constraints on a new model ensemble. **The application of the emergent constraints to CMIP6 data shows a decrease in skill and statistical significance of the emergent relationship for nearly all constraints, with this decrease being large in many cases.** Consequently, the size of the constrained ECS ranges (66% confidence intervals) widens by 51% on average in CMIP6 compared to CMIP5.

Yet NCA5 described the use of emergent constraint analysis as a great “advance” that reduced uncertainty.

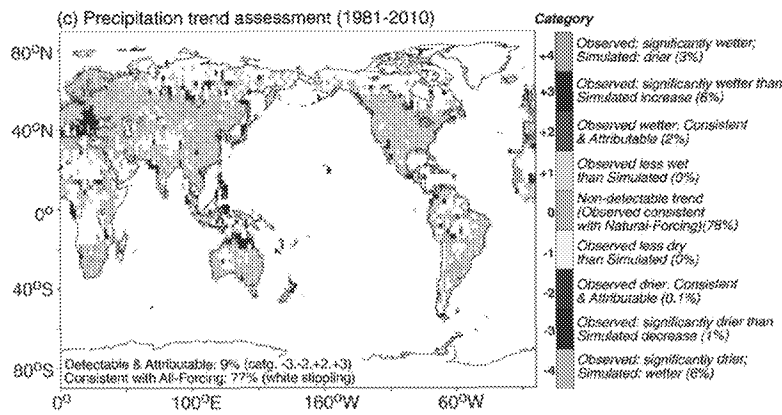
3.4 Overstating Findings in Underlying Sources

Although we did not do a detailed audit of the NCA5’s use of source material, a few spot checks turned up evidence of a pattern of overstatement.

Chapter 2 page 11 reports on an increase in precipitation in central and eastern US based on a comparison of 2002-2021 average rainfall to the average over 1901-1960. Note that this a non-standard metric; we will discuss NCA5’s inconsistent choices of time scales of analysis below. The change in this case is called a “trend” even though this is not how a trend is measured, and says that it is “attributable to climate change”. The claims were attributed to the following paper:

- Knutson, Thomas and Fanrong Zeng (2018) “Model Assessment of Observed Precipitation Trends over Land Regions: Detectable Human Influences and Possible Low Bias in Model Trends” *Journal of Climate* 31(12) [[HYPERLINK "https://journals.ametsoc.org/view/journals/clim/31/12/jcli-d-17-0672.1.xml"](https://journals.ametsoc.org/view/journals/clim/31/12/jcli-d-17-0672.1.xml)]

But Knutson and Zeng did not say these things. It examined linear trends over 1901 – 2010, 1951 – 2010 and 1981 – 2010. It did not compare average rainfall over 2002 - 2021 to average rainfall over 1901 – 1960, indeed it was published in 2018 so it could not have. With regard to 1981-2010 trends its results were summarized in the following figure:



Gray indicates no trends detected. Stippling means that there were no trends in the models either so the models and observations agreed in that respect. Detectable and attributable trends were found over only 9% of the land surface of the Earth. Over the US there are detectable trends over only a few regions in the Southwest.

Chapter 2 page 18 states

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.

This is attributed to two papers:

- Diffenbaugh, N.S., D. Singh, and J.S. Mankin, 2018: Unprecedented climate events: Historical changes, aspirational targets, and national commitments. *Science Advances*, 4 (2), 3354. [HYPERLINK "<https://doi.org/10.1126/sciadv.aao3354>"]

and

- Kirchmeier-Young, M.C. and X. Zhang, 2020: Human influence has intensified extreme precipitation in North America. *Proceedings of the National Academy of Sciences of the United States of America*, 117 (24), 13308-13313. [HYPERLINK "<https://doi.org/10.1073/pnas.1921628117>"]

Diffenbaugh et al. presented ratios of observed occurrences of extreme events to simulated occurrence rates in CMIP6 models run with only natural forcings. They report that for 79% of the U.S. extreme rainfall event frequencies are currently higher than in model simulations, and the ratio of occurrences will rise under future warming simulations. This is not "robust" evidence of anthropogenic influence since it requires readers to assume that climate models provide accurate simulations of regional precipitation patterns, something which even the IPCC AR6 admits is uncertain (AR6 WGI SPM Box SPM 1.2, SPM Section C.1.3).

Kirchmeier-Young and Zhang looked at extreme 1- and 5-day events in North America and, using 3 GCMs, found "A signal of combined anthropogenic and natural external forcing can be detected in the intensification of extreme precipitation at the continental scale over North America. In some cases, this intensification can be attributed to human influence specifically." However, they noted large differences among the three models in their simulated precipitation changes. Also, 2 of the 3 models failed to yield detection for Rx5Day for the North America mean. Finally, the authors used Total Least Squares, an estimation method known to overstate signal detection results (CWG Section 8.3.2). Here again this is not "robust" evidence, it is suggestive but other studies have found natural variability predominant. Both cited references utilized the implausible RCP8.5 scenario and began their "historical" observational records only in 1961.

4 RELIANCE ON *Ad Hoc* TIME SCALES FOR TREND ANALYSIS

In CWG25 Chapter 6 we discussed the need to be careful regarding the choice of time scale when making claims about trends in extreme weather. We gave examples from analysis of river flooding (6.1), heatwaves (6.3) and extreme precipitation (6.4) to show how assertions about apparent trends based on short data sets fall apart when looking at longer versions of the same data sets. Here we elaborate on these examples to illustrate a general point that NCA5 made inconsistent and *ad hoc* choices about time scales of analysis, weakening the validity of their conclusions.

4.1 Average and Extreme Precipitation

McKittrick and Christy (2019)⁶ showed that apparently significant positive trends in U.S. average and extreme precipitation over the NCA4 interval (1901 – 2016) disappeared on longer samples (extending back as far as the 1840s depending on location or on a shorter interval coinciding with the final 40 years of the data then available (1978 – 2017).

In CWG Section 6.4 we presented analysis of updated data for the same locations and many more besides, in all cases finding considerable regional heterogeneity and lack of robustness of trends to use of long samples.

NCA5 did not continue the NCA4 precedent of using the post-1901 interval as the time scale for its precipitation discussion, instead it refers to changes “since the 1950s” which we take to mean 1950 onwards though NCA5 Fig. 2.8 suggests 1958 as the start date. For the present report we have extended the analysis even further now to include 141 stations across the US in the Pacific Coast, Southwest, Midwest, Northeast and Southeast regions. We provide details in the Appendix; here we note merely that once again it is possible to find trends that support the NCA5 position, but they are not robust to selecting longer or shorter time scales of analysis. Data from 1950 to 2024 yields many indications of increased average and extreme precipitation at individual stations and region-wide averages. But when using the entire data set (back to the 1890s or earlier depending on location) or the later subset (1980 to 2024) the trends become smaller, in many cases they become statistically insignificant, and occasionally they change sign. Only in the Northeast region are the post-1950 trends robust to focusing on the post-1980 interval.

Under Key Message 2.2 “Extreme Events Are Becoming More Frequent and Severe” (p. 2-16) NCA5 states (p. 2-18):

“Rainfall is becoming more extreme”

Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US. This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity. The largest increase in the number of extreme precipitation days (defined as the top 1% of heaviest precipitation events) has occurred over the Northeast (an increase of around 60%) and Midwest (around 45%), along with increases of more than 10% in their annual and 5-year maximum amount

⁶ McKittrick, R., and J.R. Christy (2019). Assessing changes in US regional precipitation on multiple time scales. *Journal of Hydrology*, 578, 124074. [[HYPERLINK "https://doi.org/10.1016/j.jhydrol.2019.124074"](https://doi.org/10.1016/j.jhydrol.2019.124074)]

(Figure 2.8). These changes have contributed to increases in river and stream flooding in these regions. The increase in frequency and intensity of precipitation extremes is evident across a broad range of event durations (from 1 to 30 days) and return intervals (1 to 20 years), particularly east of the Rocky Mountains.

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US. Paleoclimate records derived from tree-ring growth provide evidence that summer moisture has increased over the past century in parts of New England, the central-eastern US, and the northern Mississippi River valley.

The following is a more accurate summary of what U.S. data show.

There are regionally-heterogeneous changes in average and extreme precipitation. Positive trends in annual average rainfall and extreme events (defined either as the annual maximum or the number of exceedances of the 99th percentile value) are generally weak or non-existent when looking at samples exceeding 130 years in length. Significant trends can be found when beginning the sample in the 1950s although in most cases the trends weaken and become insignificant when looking at the post-1980 interval. This makes attribution to anthropogenic warming difficult.

Along the Pacific coast very few stations (1 or 2 out of 29) exhibit significant trends on any time scale in any metric and the region-wide trends are insignificant. In the Southeast region about 5 out of 24 stations exhibit positive trends in average and extreme precipitation metrics and the regional trends are likewise significant, but only on samples beginning in 1950. When the sample starts in 1873 or 1980 the trends weaken and become mostly insignificant. In the Midwest region nearly half the stations exhibit positive and significant trends in average precipitation since 1893 (23/61) and 1950 (28/61) but the trends weaken after 1980: only 6/61 locations are significant and the region-wide trend is insignificant. These positive trends reflect the dryness of the 1930's Dust Bowl era. Regional trends in max and 99th percentile exceedances are insignificant post-1893 and -1980 but the latter are positive and significant post-1950.

In the Northeast region 12 out of 27 stations exhibit positive and significant increases in average precipitation post-1888, post-1950 and post-1980 (10/27) and the regional trend is positive and significant in all three intervals. The regional number of 99th percentile exceedances has a positive trend post-1950 and post-1980 but not post-1888. The significant positive trends post-1980 are concentrated in NH but are insignificant elsewhere.

Consequently, precipitation in the U.S. exhibits considerable regional and temporal variability. Relatively more places became wetter than drier. In the Midwest and Northeast the general pattern since 1950 favors increased precipitation depending on the location, although trends since 1980 have not tended to be statistically significant.

4.2 Heatwaves

- details; NCA4 used entire 20th century while NCA5 looked at post-1960 interval

5 INADEQUATE TRACEABLE ACCOUNTS

- details

6 OVERCONFIDENCE WHEN STATING CONCLUSIONS

- details

7 RELIANCE ON EXTREME SCENARIOS

-details

8 BIASED SELECTION OF REFERENCES

-details

9 SUMMARY: EVALUATING OF THE NCA5

9.1 Pertinent aspects when evaluating in light of statutory requirements

- not our remit to make a ruling but here are aspects to consider in light of statutory requirements

9.2 Evaluation from the perspective of expert users of the report

- we have deep knowledge of the topics surveyed by the NCA5 authors
- we do not have confidence that the report was balanced and comprehensive
- we can point to many specific instances in which the report did not exhibit an appropriate level of quality or integrity as a scientific document
- we have reason to believe the whole process, from author selection to handling of expert reviews, was biased towards reinforcing foregone conclusions and alarmist messaging

9.3 Evaluation from the perspective of citizens interested in good policymaking

- Public concerns about climate change are valid, as are concerns about cost of living, economic growth, employment, etc.
- We share the general concern that elected officials and those who serve them have the best information available when making important decisions around energy and climate policy
- NCA5 was a missed opportunity: it could have been a valuable input to that process but it did not turn out that way
- consequently its usage is unlikely to lead to better decisions and would more likely increase the error rate in policy formation and we recommend it not be used for policymaking purposes.

APPENDIX 1: Seth's letter on statutory requirements for NCA5

APPENDIX 2: Analysis of 141 U.S. Longterm Daily Precipitation Records.

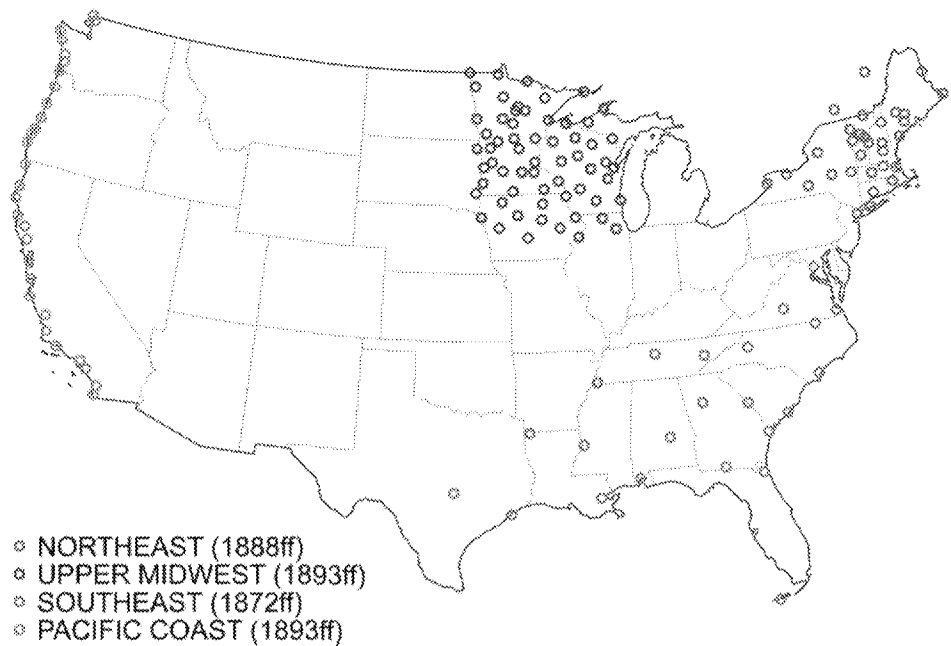


Figure. Stations used in the following analyses.

Table codes: (-) neg insignificant, -- neg significant, (+) pos insignificant, ++ pos significant.

Column 1: Measure
Column 2: Number of stations in that region
Column 3: Count of stations exhibiting a significant positive trend
Column 3: Count of stations exhibiting a significant negative trend
Column 5: Characteristic of region-wide trend

PACIFIC COAST

Since 1893:

	No. stns	+ trends	- trends	region
1-day average	29	0	1	(-)
2-day average	29	0	1	(-)
Avg on non-zero days	29	0	9	--
Variability	29	1	0	(+)
Annual max	29	2	1	(+)

Number of 99 th pct exceedances	29	1	0	(-)
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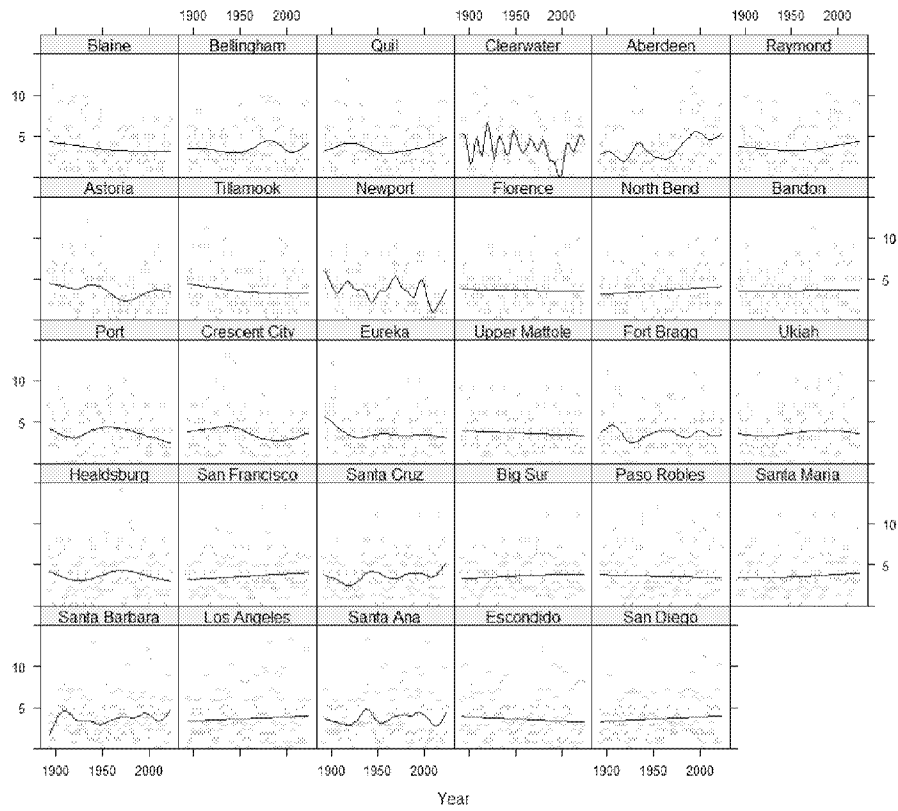
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	29	0	1	(-)
2-day average	29	0	1	(-)
Avg on non-zero days	29	0	4	(-)
Variability	29	2	3	(-)
Annual max	29	6	3	(-)
Number of 99 th pct exceedances	29	2	1	(-)

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	29	0	0	(-)
2-day average	29	0	0	(-)
Avg on non-zero days	29	0	1	(-)
Variability	29	0	0	(-)
Annual max	29	2	1	(-)
Number of 99 th pct exceedances	29	0	0	(+)

Annual No. 99th Percentile Exceedances PC 1893-2024



SOUTHEAST

Since 1873:

	No. stns	+ trends	- trends	region
1-day average	24	1	1	(+)
2-day average	24	1	1	(+)
Avg on non-zero days	24	7	2	(+)
Variability	24	1	0	(+)
Annual max	24	2	0	(+)
Number of 99 th pct exceedances	24	5	0	(+)

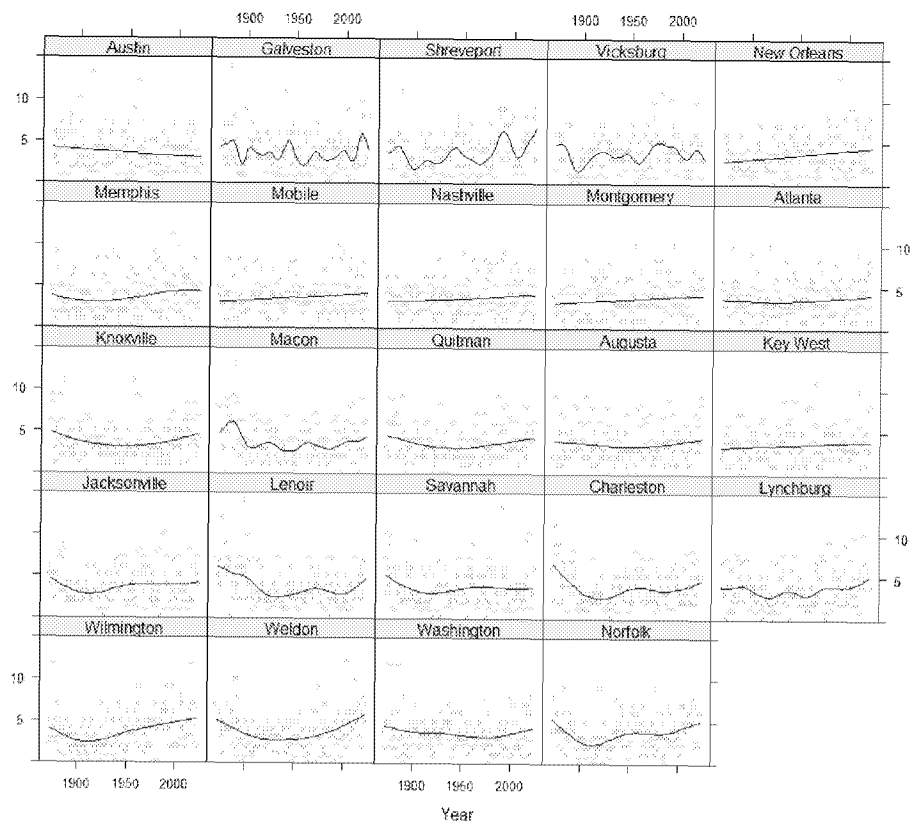
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	24	5	0	++
2-day average	24	5	0	++
Avg on non-zero days	24	5	1	++
Variability	24	6	0	++
Annual max	24	4	0	++
Number of 99 th pct exceedances	24	4	0	(+)

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	24	5	0	(+)
2-day average	24	5	0	(+)
Avg on non-zero days	24	5	1	(+)
Variability	24	3	0	(+)
Annual max	24	4	0	(+)
Number of 99 th pct exceedances	24	4	0	(+)

Annual No. 99th Percentile Exceedances SE 1873-2024



MIDWEST

Since 1893:

	No. stns	+ trends	- trends	region
1-day average	61	23	0	++
2-day average	61	23	0	++
Avg on non-zero days	61	2	12	(+)
Variability	61	12	0	++
Annual max	61	9	0	(+)
Number of 99 th pct exceedances	61	10	0	(+)

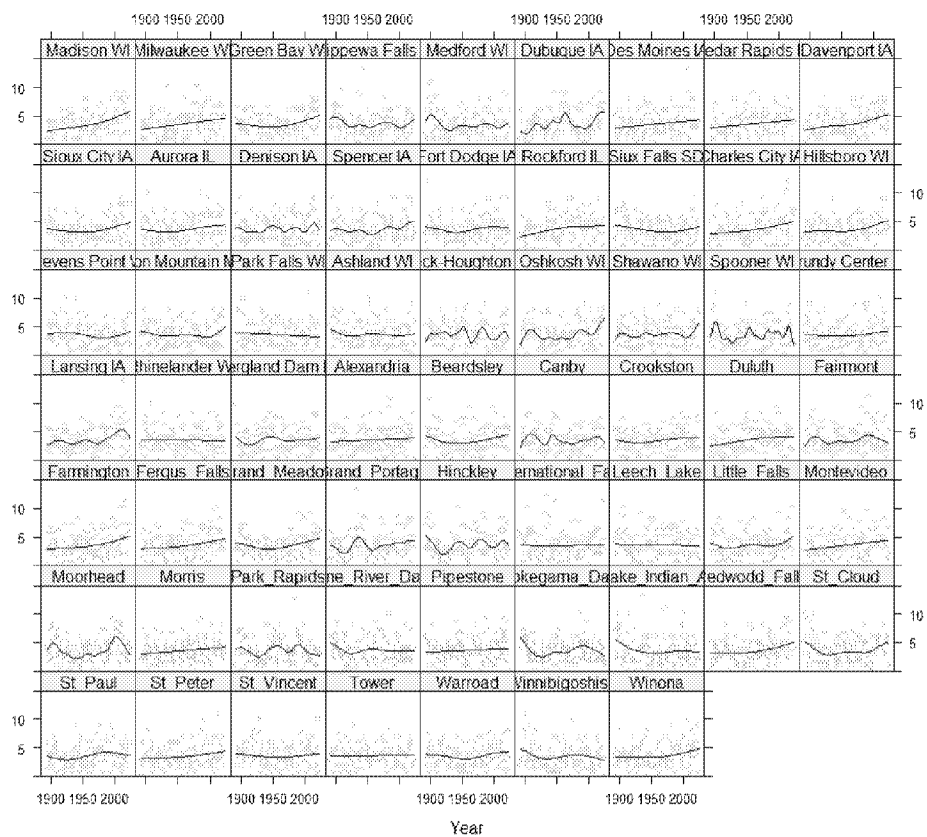
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	61	28	2	++
2-day average	61	28	2	++
Avg on non-zero days	61	11	1	++
Variability	61	16	0	(+)
Annual max	61	8	0	(+)
Number of 99 th pct exceedances	61	19	0	++

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	61	6	1	(+)
2-day average	61	6	1	(+)
Avg on non-zero days	61	8	2	(+)
Variability	61	5	1	(+)
Annual max	61	0	1	(+)
Number of 99 th pct exceedances	61	5	3	(-)

Annual No. 99th Percentile Exceedances MW 1893-2024



NORTHEAST

Since 1888:

	No. stns	+ trends	- trends	region
1-day average	27	12	0	++
2-day average	27	12	0	++
Avg on non-zero days	27	7	1	(+)
Variability	27	4	0	(+)
Annual max	27	3	0	(-)
Number of 99 th pct exceedances	27	5	0	(+)

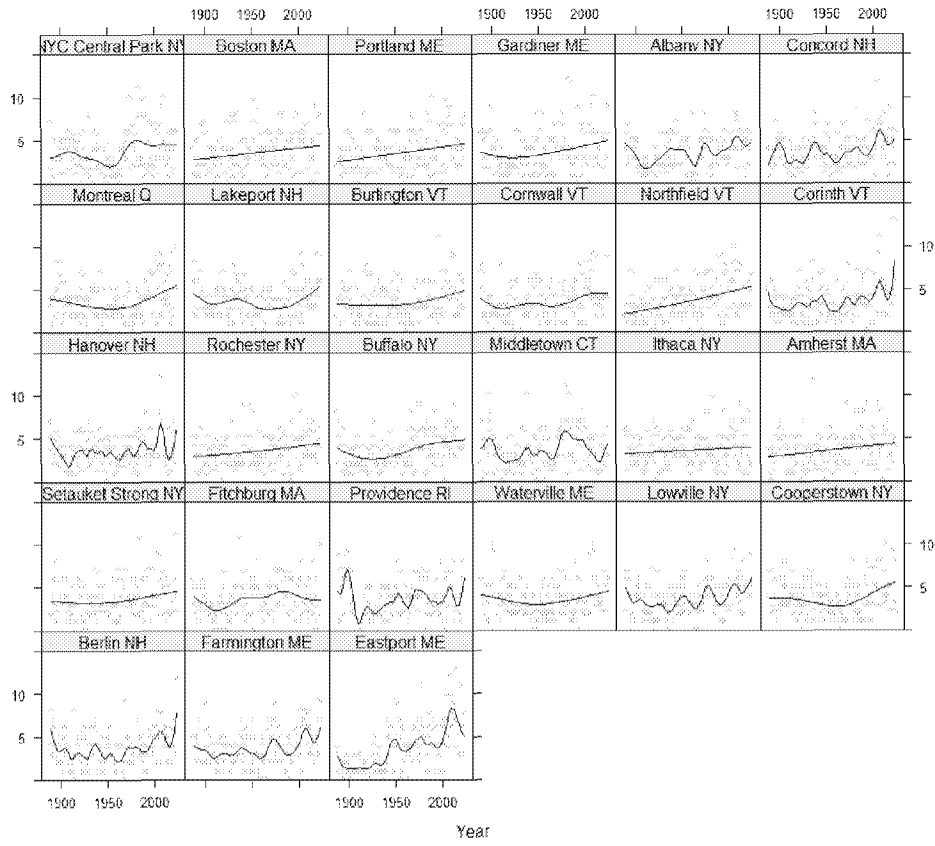
Since 1950:

	No. stns	+ trends	- trends	region
1-day average	27	12	0	++
2-day average	27	12	0	++
Avg on non-zero days	27	7	1	(+)
Variability	27	4	0	(+)
Annual max	27	3	0	(-)
Number of 99 th pct exceedances	27	5	0	++

Since 1980:

	No. stns	+ trends	- trends	region
1-day average	27	10	1	++
2-day average	27	10	1	++
Avg on non-zero days	27	6	0	(+)
Variability	27	2	0	(+)
Annual max	27	1	0	(+)
Number of 99 th pct exceedances	27	1	1	++

Annual No. 99th Percentile Exceedances NE 1888-2024



Scenario	Year	Crop demand	Energy crop demand	Livestock demand	Energy crop production	Non-energy crop production
SSP1 - 1.9	2005	3389946625		238986475.6	31469668.7	3417340000
SSP1 - 1.9	2010	3780159000		262440747.1	56039029.3	3813367000
SSP1 - 1.9	2020	4330961000		289096841.8	91136859.74	4354620000
SSP1 - 1.9	2030	4764790750		309853936.5	445930839.8	4944219000
SSP1 - 1.9	2040	5110124250		324523696.3	1574852336	5147676000
SSP1 - 1.9	2050	5455829250		339193526.4	2006291953	5456159000
SSP1 - 1.9	2060	5464465625		332888770.5	2870823938	5464506000
SSP1 - 1.9	2070	5473166625		326584119.1	4050276313	5473212000
SSP1 - 1.9	2080	5481933875		320279377.9	5564746500	5481968000
SSP1 - 1.9	2090	5490764875		313974711.9	6731205375	5490793000
SSP1 - 1.9	2100	5499663000		307670098.6	8014704250	5499687000
SSP1 - 2.6	2005	3389946625		238986475.6	31469668.7	3417340000
SSP1 - 2.6	2010	3780159000		262440747.1	56039029.3	3813367000
SSP1 - 2.6	2020	4330961000		289096841.8	95187658.69	4355897000
SSP1 - 2.6	2030	4764790750		309853936.5	161969332.5	4827157000
SSP1 - 2.6	2040	5110124250		324523696.3	399864022.5	5254736000
SSP1 - 2.6	2050	5455829250		339193526.4	808240431.6	5477702000
SSP1 - 2.6	2060	5464465625		332888770.5	1637018906	5471201000
SSP1 - 2.6	2070	5473166625		326584119.1	2995031625	5479598000
SSP1 - 2.6	2080	5481933875		320279377.9	5202315750	5486188000
SSP1 - 2.6	2090	5490764875		313974711.9	7526928500	5495285000
SSP1 - 2.6	2100	5499663000		307670098.6	7748012625	5509088000
SSP1 - 3.4	2005	3389946625		238986475.6	31469668.7	3417340000
SSP1 - 3.4	2010	3780159000		262440747.1	56039029.3	3813367000
SSP1 - 3.4	2020	4334602375		289174832	109423546.9	4361476000
SSP1 - 3.4	2030	4776535875		310123299.8	215929142.1	4852597000
SSP1 - 3.4	2040	5130602250		324986742.2	421916095.2	5309377000
SSP1 - 3.4	2050	5485054125		339850246.1	758487498	5519592000
SSP1 - 3.4	2060	5494617875		333571646.5	1241709566	5508623000
SSP1 - 3.4	2070	5504243500		327292790	2014145227	5519789000
SSP1 - 3.4	2080	5513932500		321014147.5	3242520125	5529474000
SSP1 - 3.4	2090	5523683375		314735501	6014199125	5538850000
SSP1 - 3.4	2100	5533499500		308456711.9	8482560250	5548808000
SSP1 - 4.5	2005	3389946625		238986475.6	31469668.7	3417340000
SSP1 - 4.5	2010	3780159000		262440747.1	56039029.3	3813367000
SSP1 - 4.5	2020	4339871875		289206884.8	121538069.8	4365692000
SSP1 - 4.5	2030	4789960750		310242688.5	302516750	4833716000

SSP1 - 4.5	2040	5153440375	325304516.6	571864125.5	5291867000
SSP1 - 4.5	2050	5517297625	340366303.7	906001980.5	5544530000
SSP1 - 4.5	2060	5527588625	334133506.8	1308092318	5539393000
SSP1 - 4.5	2070	5537941500	327900635.7	1974305289	5552553000
SSP1 - 4.5	2080	5548358500	321667820.3	2992365000	5566294000
SSP1 - 4.5	2090	5558838000	315435009.8	3964526844	5577937000
SSP1 - 4.5	2100	5569383250	309202231.4	4540259125	5588570000
SSP1 - Bas	2005	3389946625	238986475.6	31469668.7	3417340000
SSP1 - Bas	2010	3780159000	262440747.1	56039029.3	3813367000
SSP1 - Bas	2020	4347582125	289282287.1	122898720.7	4373590000
SSP1 - Bas	2030	4808445875	310456300.8	310195404.3	4849270000
SSP1 - Bas	2040	5181673375	325796189.5	588363849.6	5320158000
SSP1 - Bas	2050	5555269875	341136144.5	906566365.2	5582935000
SSP1 - Bas	2060	5566552250	334972203.1	1233003105	5578910000
SSP1 - Bas	2070	5577899250	328808197.3	1923219180	5594197000
SSP1 - Bas	2080	5589310125	322644175.8	2882637469	5610093000
SSP1 - Bas	2090	5600786875	316480181.6	3780147672	5624206000
SSP1 - Bas	2100	5612326250	310316118.2	3976263906	5635640000
SSP2 - 1.9	2005	2562601266	216129997	0	2734478368
SSP2 - 1.9	2010	2743381807	233117496.4	0	3032884054
SSP2 - 1.9	2020	3240968703	274615831.9	938601454.5	3533324392
SSP2 - 1.9	2030	3680531207	312901169.3	1792971341	3973154860
SSP2 - 1.9	2040	3835749663	320698974.2	3058171341	4128231931
SSP2 - 1.9	2050	3776165098	310942612	4619314897	4068085715
SSP2 - 1.9	2060	3565781095	291049273.4	6366850246	3856034496
SSP2 - 1.9	2070	3431014635	276707794.1	7900094276	3720025280
SSP2 - 1.9	2080	3261283723	261323786.7	9106460399	3549695631
SSP2 - 1.9	2090	3089132872	244389578.4	9954286409	3375412830
SSP2 - 1.9	2100	2903320664	226570798.3	10581315270	3183984473
SSP2 - 2.6	2005	2562601266	216129997	0	2734478368
SSP2 - 2.6	2010	2743381807	233117496.4	0	3032884054
SSP2 - 2.6	2020	3237874875	274382410.3	1026868121	3530230798
SSP2 - 2.6	2030	3721526037	315811043.4	1586571341	4014150642
SSP2 - 2.6	2040	4068857235	345656412.3	2245571341	4361486744
SSP2 - 2.6	2050	4282110196	360684725.3	3073904674	4574683211
SSP2 - 2.6	2060	4330660741	360853169.3	4237971705	4623033265
SSP2 - 2.6	2070	4305793128	357231063.5	5901253250	4597730598
SSP2 - 2.6	2080	4203009592	346840839.2	7654804470	4494383185
SSP2 - 2.6	2090	4023176428	331033307.7	9015083390	4313713465
SSP2 - 2.6	2100	3818645969	314039959.7	9983781970	4107834920
SSP2 - 3.4	2005	2562601266	216129997	0	2734478368
SSP2 - 3.4	2010	2743381807	233117496.4	0	3032884054
SSP2 - 3.4	2020	3246219174	275496711.7	938601454.5	3538613994
SSP2 - 3.4	2030	3739180838	317292079.3	1160838008	4031805506
SSP2 - 3.4	2040	4127857896	350854242.4	1607838008	4420509913
SSP2 - 3.4	2050	4420510815	374643894.9	2344971341	4713160261
SSP2 - 3.4	2060	4578887569	386990181.1	3281704674	4871483411

SSP2 - 3.4	2070	4652700094		392618684.7	4414305039	4945195476
SSP2 - 3.4	2080	4641985423		392091972.9	5942412463	4934266125
SSP2 - 3.4	2090	4517722522		381399372.7	7413937803	4809698138
SSP2 - 3.4	2100	4337699238		365387690.3	8598271136	4628869734
SSP2 - 4.5	2005	2562601266		216129997	0	2734478368
SSP2 - 4.5	2010	2743381807		233117496.4	0	3032884054
SSP2 - 4.5	2020	3248917997		275839084.9	938601454.5	3541323517
SSP2 - 4.5	2030	3745438630		317729576.9	1058571341	4038069092
SSP2 - 4.5	2040	4159658312		352634669	1304838008	4452318462
SSP2 - 4.5	2050	4492174743		380686753.4	1709238008	4784848480
SSP2 - 4.5	2060	4712009911		399023954	2318038008	5004669273
SSP2 - 4.5	2070	4834685184		409914104	3309945797	5127300778
SSP2 - 4.5	2080	4875660229		414819297.5	4596479130	5168194521
SSP2 - 4.5	2090	4818471005		411139333.4	5835726789	5110846865
SSP2 - 4.5	2100	4687290137		401639483.2	6815054091	4979390465
SSP2 - 6.0	2005	2562601266		216129997	0	2734478368
SSP2 - 6.0	2010	2743381807		233117496.4	0	3032884054
SSP2 - 6.0	2020	3251815303		276120344	938601454.5	3544221721
SSP2 - 6.0	2030	3747678810		318008550.7	1029038008	4040308540
SSP2 - 6.0	2040	4176345414		354213553.9	1085571341	4469005322
SSP2 - 6.0	2050	4536363588		383735170.7	1237838008	4829049200
SSP2 - 6.0	2060	4809400776		406764621.9	1790504674	5102106487
SSP2 - 6.0	2070	4986592736		422765346.2	2347505039	5279289678
SSP2 - 6.0	2080	5082883306		432640241.9	2878479130	5375548171
SSP2 - 6.0	2090	5120586811		437128596.9	3357212463	5413196873
SSP2 - 6.0	2100	5070522839		435639160.9	3875204267	5363053826
SSP2 - Bas	2005	2562601266		216129997	0	2734478368
SSP2 - Bas	2010	2743381807		233117496.4	0	3032884054
SSP2 - Bas	2020	3254604910		276592207.6	938601454.5	3547035356
SSP2 - Bas	2030	3748450305		318148911.2	1029038008	4041098202
SSP2 - Bas	2040	4180407480		354609432.5	1085571341	4473086071
SSP2 - Bas	2050	4548648170		384838090.8	1244971341	4841352055
SSP2 - Bas	2060	4836569216		409034747.9	1711838008	5129282933
SSP2 - Bas	2070	5032566591		426433917.4	2294504674	5325285643
SSP2 - Bas	2080	5171049715		439297008.6	2786279130	5463747167
SSP2 - Bas	2090	5265445917		447270074.8	3212612463	5558108145
SSP2 - Bas	2100	5302376806		451089114.2	3580279131	5594997470
SSP3 - 3.4	2005	2274624100	0	246084000	0	3254988500
SSP3 - 3.4	2010	2638405600	207424500	270010500	0	3546514000
SSP3 - 3.4	2020	3346379800	563275100	317845300	23807300	4124060500
SSP3 - 3.4	2030	4555102100	1586371500	355994500	94732000	4733432700
SSP3 - 3.4	2040	9528768500	7402989100	381268700	1071635300	5301054400
SSP3 - 3.4	2050	1.83E+10	17992488300	401796500	3068492000	5786625400
SSP3 - 3.4	2060	2.5394E+10	26523962900	419259500	4661989800	6222629000
SSP3 - 3.4	2070	3.5933E+10	39375695900	434614600	7167183100	6600240800
SSP3 - 3.4	2080	4.2857E+10	47720115000	449019900	8802562900	6930666100
SSP3 - 3.4	2090	4.8456E+10	54416968000	461911900	10140013100	7225136600

SSP3 - 3.4	2100	5.254E+10	59214813000	473973200	11122271200	7506876700
SSP3 - 4.5	2005	2274624100	0	246084000	0	3254988500
SSP3 - 4.5	2010	2638405600	207424500	270010500	0	3546514000
SSP3 - 4.5	2020	3346379800	563275100	317845300	23807300	4124060500
SSP3 - 4.5	2030	4334357800	1308262100	356197800	78865500	4696965700
SSP3 - 4.5	2040	7100780500	4357552800	383253300	569242400	5207008600
SSP3 - 4.5	2050	1.426E+10	12924807400	405031800	2149181000	5708250500
SSP3 - 4.5	2060	2.4894E+10	25872437300	422248000	4568162000	6213920600
SSP3 - 4.5	2070	2.8874E+10	30511765800	439808400	5402502400	6623522300
SSP3 - 4.5	2080	3.4127E+10	36738348000	456706400	6607696600	6984669600
SSP3 - 4.5	2090	3.9657E+10	43321945700	471661200	7938064700	7287429600
SSP3 - 4.5	2100	4.6153E+10	51128708300	484256100	9519297300	7575811500
SSP3 - 6.0	2005	2274624100	0	246084000	0	3254988500
SSP3 - 6.0	2010	2638405600	207424500	270010500	0	3546514000
SSP3 - 6.0	2020	3346379800	563275100	317845300	23807300	4124060500
SSP3 - 6.0	2030	4322101800	1292808800	356208900	77975800	4694950500
SSP3 - 6.0	2040	6725491200	3885274800	383866700	495259600	5191114100
SSP3 - 6.0	2050	1.2536E+10	10763098200	406531800	1756074100	5676127200
SSP3 - 6.0	2060	1.884E+10	18285814500	426101500	3148049600	6131327800
SSP3 - 6.0	2070	2.5992E+10	26873695300	444496000	4760068500	6571400300
SSP3 - 6.0	2080	3.0861E+10	32607824600	462349700	5824427100	6985566500
SSP3 - 6.0	2090	3.4918E+10	37324825400	479432700	6713919300	7378238300
SSP3 - 6.0	2100	4.0564E+10	44021687900	495667000	8013229100	7769912000
SSP3 - Bas	2005	2274624100	0	246084000	0	3254988500
SSP3 - Bas	2010	2639070000	208276400	270004500	0	3546642500
SSP3 - Bas	2020	3331128200	543713500	317867200	22811500	4121289300
SSP3 - Bas	2030	4221368300	1165691900	356336400	59736300	4688856900
SSP3 - Bas	2040	5306526100	2108307500	384612200	147776500	5187355300
SSP3 - Bas	2050	6859370600	3665047700	408098000	346547600	5663504100
SSP3 - Bas	2060	8613413500	5505120900	428164000	610618400	6099001000
SSP3 - Bas	2070	1.057E+10	7601542900	447496900	950184300	6502512900
SSP3 - Bas	2080	1.2466E+10	9614233500	466442000	1299555400	6887710300
SSP3 - Bas	2090	1.3999E+10	11167458400	484770400	1579741300	7260640500
SSP3 - Bas	2100	1.581E+10	13059988700	502721500	1932907900	7639074400
SSP4 - 2.6	2005					
SSP4 - 2.6	2010	3256111096	1395044483	193120081.3	0	3480772607
SSP4 - 2.6	2020	3688065943	2055162772	226782507.4	416119337.7	3733450529
SSP4 - 2.6	2030	4056775148	4258197145	249934204.3	1415325744	4106028838
SSP4 - 2.6	2040	4337267449	5901712417	268136529.4	2632015002	4390872346
SSP4 - 2.6	2050	4536958025	7638197466	282536393.6	3811926627	4618779235
SSP4 - 2.6	2060	4621558929	10530066280	287200487.6	5839342348	4791391396
SSP4 - 2.6	2070	4631168732	13720115300	286203612.4	7744104124	4919074582
SSP4 - 2.6	2080	4574436826	16720568310	280748814.5	9427417241	4823136164
SSP4 - 2.6	2090	4460587084	19412784120	270089955.8	10794232500	4507491963
SSP4 - 2.6	2100	4320295803	23382926660	257851582.8	11875246740	4339484585
SSP4 - 3.4	2005					
SSP4 - 3.4	2010	3256111096	1395044483	193120081.3	0	3480772608

SSP4 - 3.4	2020	3688065943	2055162772	226782507.4	416119349.5	3733450818
SSP4 - 3.4	2030	4065408416	3463103048	251364275.2	809967869.6	4111201746
SSP4 - 3.4	2040	4366079065	4499070945	271523728.1	1401410885	4411540553
SSP4 - 3.4	2050	4599917934	5460304167	288599036.2	2030468052	4649384202
SSP4 - 3.4	2060	4717078697	7157216458	295632702.3	3319492453	4790891641
SSP4 - 3.4	2070	4764389428	9439653165	297221030.5	4981006890	4901687526
SSP4 - 3.4	2080	4743325249	12504323010	293813742.2	7006761445	4998394008
SSP4 - 3.4	2090	4640694514	15652634050	284739256.4	8872495698	4950759336
SSP4 - 3.4	2100	4520489840	18310555540	273574855.9	10415977160	4656175021
SSP4 - 4.5	2005					
SSP4 - 4.5	2010	3256111096	1395044483	193120081.3	0	3480772608
SSP4 - 4.5	2020	3688065943	2055162772	226782507.4	416119349.5	3733450818
SSP4 - 4.5	2030	4069388299	3134398163	252019096.3	694478796.2	4114065334
SSP4 - 4.5	2040	4379321638	4069379209	273209268.5	1026342599	4423510300
SSP4 - 4.5	2050	4631730624	4764042079	291829345.3	1439663950	4676678990
SSP4 - 4.5	2060	4768264870	5779588519	300213929.5	2191441997	4821543573
SSP4 - 4.5	2070	4840582218	7101882306	303464075.8	3189633018	4917135902
SSP4 - 4.5	2080	4919420978	7667474162	307518762.8	3603229438	5022206403
SSP4 - 4.5	2090	4940141114	8004922179	306890861.3	3861042914	5063430600
SSP4 - 4.5	2100	4921290329	8938689741	303336930	4582757083	5083913288
SSP4 - 6.0	2005					
SSP4 - 6.0	2010	3256111096	1395044483	193120081.3	0	3480772608
SSP4 - 6.0	2020	3688065943	2055162772	226782507.4	416119349.5	3733450818
SSP4 - 6.0	2030	4075308094	2719598698	252973984.1	575134101.5	4118197255
SSP4 - 6.0	2040	4400629550	3350646210	275974186.1	747468307.6	4444520472
SSP4 - 6.0	2050	4681811061	3871040683	297647864.3	894189174.5	4726210114
SSP4 - 6.0	2060	4861749764	4462581725	309141212.1	1101942473	4908311613
SSP4 - 6.0	2070	4990659644	4722943634	316251769.1	1228501030	5039111504
SSP4 - 6.0	2080	5075092902	4938958937	319763915.7	1373609897	5126279379
SSP4 - 6.0	2090	5091903767	5132000307	318052955.6	1530004098	5147582389
SSP4 - 6.0	2100	5086261651	5471607722	314753919.2	1819424521	5152509904
SSP4 - Bas	2005				0	3097622458
SSP4 - Bas	2010				0	3480772608
SSP4 - Bas	2020				377877064.1	3731899247
SSP4 - Bas	2030				590799514.6	4122075488
SSP4 - Bas	2040				794897032.3	4453221493
SSP4 - Bas	2050				955881565.5	4749315991
SSP4 - Bas	2060				1169169265	4940717374
SSP4 - Bas	2070				1246357131	5090665457
SSP4 - Bas	2080				1297554051	5205640017
SSP4 - Bas	2090				1310590368	5263731014
SSP4 - Bas	2100				1310732448	5314130224
SSP5 - 1.9	2005		25325500	205757600	25325500	3327675000
SSP5 - 1.9	2010		11213800	235413800	11213800	3758394200
SSP5 - 1.9	2020		83659900	303699700	83659900	4525046700
SSP5 - 1.9	2030		394567300	382277900	394567300	4953645200
SSP5 - 1.9	2040		5939708200	463265700	5939708200	5364107000

SSP5 - 1.9	2050	15281369200	520819300	15281369200	5828327900
SSP5 - 1.9	2060	17786588100	555408400	17786588100	6174538200
SSP5 - 1.9	2070	19348541000	572768000	19348541000	6417277200
SSP5 - 1.9	2080	20623793500	573378800	20623793500	6451233300
SSP5 - 1.9	2090	20715263700	558313300	20715263700	6365479100
SSP5 - 1.9	2100	20914702600	526916100	20914702600	6159845700
SSP5 - 2.6	2005	25325500	205757500	25325500	3327677400
SSP5 - 2.6	2010	11213800	235444900	11213800	3758809400
SSP5 - 2.6	2020	83659900	304184700	83659900	4527751900
SSP5 - 2.6	2030	129415800	382473000	129415800	4946967800
SSP5 - 2.6	2040	1316341200	460410300	1316341200	5317633100
SSP5 - 2.6	2050	7409837300	515365200	7409837300	5753868500
SSP5 - 2.6	2060	14742592600	548486200	14742592600	6052379200
SSP5 - 2.6	2070	17720538700	566200900	17720538700	6333484500
SSP5 - 2.6	2080	19564870900	569582500	19564870900	6361395800
SSP5 - 2.6	2090	21543209900	557599900	21543209900	6314436100
SSP5 - 2.6	2100	23142312000	530170700	23142312000	6170332500
SSP5 - 3.4	2005	25325500	205757500	25325500	3327677400
SSP5 - 3.4	2010	11213800	235444900	11213800	3758809400
SSP5 - 3.4	2020	83659900	304184700	83659900	4527751900
SSP5 - 3.4	2030	74239100	386507800	74239100	4950724100
SSP5 - 3.4	2040	109734000	460248100	109734000	5335194400
SSP5 - 3.4	2050	1157429900	514826600	1157429900	5716099500
SSP5 - 3.4	2060	5030808100	546835200	5030808100	6003412000
SSP5 - 3.4	2070	9704882200	562247800	9704882200	6179976400
SSP5 - 3.4	2080	14470651000	563882300	14470651000	6239495900
SSP5 - 3.4	2090	18761840600	551415000	18761840600	6211186900
SSP5 - 3.4	2100	19915488200	526742700	19915488200	6163501900
SSP5 - 4.5	2005	25325500	205757500	25325500	3327677400
SSP5 - 4.5	2010	11213800	235444900	11213800	3758809400
SSP5 - 4.5	2020	83659900	304184700	83659900	4527751900
SSP5 - 4.5	2030	150668900	386503200	150668900	4950044500
SSP5 - 4.5	2040	290556700	466501500	290556700	5329383300
SSP5 - 4.5	2050	1161593700	514563500	1161593700	5713119500
SSP5 - 4.5	2060	3640707100	546391600	3640707100	5987242400
SSP5 - 4.5	2070	6093771000	561872000	6093771000	6141264400
SSP5 - 4.5	2080	7813299700	561299700	7813299700	6245597000
SSP5 - 4.5	2090	9197138000	546428900	9197138000	6180184300
SSP5 - 4.5	2100	9364927000	519190000	9364927000	6053412500
SSP5 - 6.0	2005	25325500	205757500	25325500	3327677400
SSP5 - 6.0	2010	11213800	235444900	11213800	3758809400
SSP5 - 6.0	2020	83659900	304184700	83659900	4527751900
SSP5 - 6.0	2030	74863100	386616700	74863100	4949998700
SSP5 - 6.0	2040	68809800	467425800	68809800	5333209800
SSP5 - 6.0	2050	58666700	521808800	58666700	5766910000
SSP5 - 6.0	2060	136672100	556845100	136672100	6059344900
SSP5 - 6.0	2070	240499400	570324700	240499400	6211292400

SSP5 - 6.0	2080	325319900	560996900	325319900	6313681400
SSP5 - 6.0	2090	603295700	545549300	603295700	6299093700
SSP5 - 6.0	2100	1246222200	517856900	1246222200	6174619000
SSP5 - Bas	2005	25325500	205757600	25325500	3327675000
SSP5 - Bas	2010	11213800	235413800	11213800	3758394200
SSP5 - Bas	2020	84564500	304241300	84564500	4523136000
SSP5 - Bas	2030	87532000	385223300	87532000	4942283400
SSP5 - Bas	2040	66829400	465109600	66829400	5320627700
SSP5 - Bas	2050	31205900	517348100	31205900	5759041800
SSP5 - Bas	2060	34324900	545685900	34324900	6029989800
SSP5 - Bas	2070	23590300	559745300	23590300	6208571100
SSP5 - Bas	2080	17276100	558366700	17276100	6308108600
SSP5 - Bas	2090	58895100	543481600	58895100	6297922900
SSP5 - Bas	2100	189018000	516273100	189018000	6197840500

Livestock production	Carbon price	Methane concentra tion	CO2 concentrat ion	Nitrous oxide concentration	Economic consumpti on	Economic consumption (\$)	Electricity capacity	Biomass capacity
238986500	0	1753.16	379.85	319.855	34531.7	3.4532E+13	3797.849	66.79926
262440781	0	1812.864	390.5053	323.68957	40443	4.0443E+13	4523.66	80.58772
289096875	0	1812.021	412.142	330.4511	60738.12	6.0738E+13	5775.863	185.2419
309853906	303.6736	1631.172	424.6815	335.06455	94211.73	9.4212E+13	5656.165	223.6486
324523656	546.2075	1449.081	425.5272	337.95418	136888.2	1.3689E+14	8287.41	315.4962
339193531	651.0314	1325.072	420.4756	340.41814	181033.2	1.8103E+14	12255.13	429.8082
332888750	707.6402	1250.522	413.8763	342.5171	220858.8	2.2086E+14	14395.68	577.2766
326584125	652.1972	1212.159	406.7838	344.55001	259777.6	2.5978E+14	14604.41	665.2974
320279438	519.7958	1180.458	398.6285	346.6581	294820.9	2.9482E+14	15802.23	711.3799
313974688	335.337	1149.776	389.0571	348.81946	326094.8	3.2609E+14	16652.92	742.3571
307670063	238.8175	1122.537	377.8966	350.98969	352095.3	3.521E+14	16096.66	823.8782
238986500	0	1753.16	379.85	319.855	34531.7	3.4532E+13	3797.849	66.79926
262440781	0	1812.864	390.5053	323.68957	40443	4.0443E+13	4523.677	77.9239
289096875	8.815058	1825.457	414.5497	330.53829	60738.12	6.0738E+13	5988.858	98.95163
309853906	32.72195	1682.249	436.5426	335.65605	94211.73	9.4212E+13	7658.348	97.17514
324523656	71.76319	1519.876	452.2906	339.02523	136888.2	1.3689E+14	9966.742	119.6849
339193531	99.9675	1399.942	460.6929	341.45747	181033.2	1.8103E+14	13132.94	239.4739
332888750	109.9755	1323.012	462.9022	343.47673	220858.8	2.2086E+14	15596.44	453.1193
326584125	148.1949	1271.819	460.6425	345.3853	259777.6	2.5978E+14	17002.01	552.336
320279438	242.5839	1218.766	453.8621	347.39661	294820.9	2.9482E+14	17462.69	671.9833
313974688	185.9612	1176.121	443.0907	349.76675	326094.8	3.2609E+14	16869.16	726.1218
307670063	139.7415	1147.289	432.1714	352.18893	352095.3	3.521E+14	18843.58	549.8993
238986500	0	1753.16	379.85	319.855	34531.7	3.4532E+13	3797.849	66.79926
262440781	0	1812.864	390.5053	323.68957	40443	4.0443E+13	4523.683	77.45602
289174781	0.581091	1873.121	415.1411	330.89811	60738.12	6.0738E+13	6059.375	92.20828
310123281	5.429163	1805.508	440.2962	337.18927	94211.73	9.4212E+13	7996.874	83.13839
324986813	16.70841	1655.813	463.8594	341.99197	136888.2	1.3689E+14	10562.71	57.22467
339850250	22.9549	1528.223	484.0237	345.35377	181033.2	1.8103E+14	14482.27	33.87289
333571594	32.80486	1439.063	499.883	347.75557	220858.8	2.2086E+14	17447.77	22.50634
327292813	61.89357	1357.795	510.1736	349.53688	259777.6	2.5978E+14	19605.84	24.61589
321014156	117.0125	1279.19	512.5219	350.96796	294820.9	2.9482E+14	20277.72	128.4759
314735500	137.5331	1213.912	505.941	352.59674	326094.8	3.2609E+14	19201.58	466.705
308456750	109.8531	1173.123	494.1748	354.75319	352095.3	3.521E+14	19081.28	563.5472
238986500	0	1753.16	379.85	319.855	34531.7	3.4532E+13	3797.849	66.79926
262440781	0	1812.864	390.5053	323.68957	40443	4.0443E+13	4523.684	77.38485
289206813	0.555831	1877.987	415.2466	330.92228	60738.12	6.0738E+13	6068.441	91.82623
310242688	0.81623	1840.18	441.2687	337.48254	94211.73	9.4212E+13	8032.07	77.22823

325304500	3.516333	1744.674	467.459	343.16175	136888.2	1.3689E+14	10718.09	42.19052
340366281	3.035026	1653.497	492.6737	348.03006	181033.2	1.8103E+14	14647.24	19.05672
334133469	7.290082	1575.082	516.0629	351.9978	220858.8	2.2086E+14	18031.06	8.565082
327900656	15.59974	1488.02	536.3393	354.80745	259777.6	2.5978E+14	21018.01	9.012983
321667844	29.58919	1394.327	551.1038	356.54991	294820.9	2.9482E+14	22692.61	7.202462
315435063	45.20924	1305.92	559.8281	357.64416	326094.8	3.2609E+14	22780.28	8.170709
309202250	46.74554	1231.064	563.6224	358.4312	352095.3	3.521E+14	21798.34	10.44637
238986500	0	1753.16	379.85	319.855	34531.7	3.4532E+13	3797.849	66.79926
262440781	0	1812.864	390.5053	323.68957	40443	4.0443E+13	4523.684	77.37998
289282281	0	1888.198	415.3473	330.99404	60738.12	6.0738E+13	6069.227	91.68074
310456313	0	1919.771	442.3016	337.94414	94211.73	9.4212E+13	8037.996	78.89134
325796219	0	1935.294	470.4785	344.412	136888.2	1.3689E+14	10769.04	45.04761
341136156	0	1915.28	498.1738	350.15178	181033.2	1.8103E+14	14619.31	20.84762
334972156	0	1864.652	524.9761	355.07787	220858.8	2.2086E+14	18047.77	9.974223
328808188	0	1797.688	550.8283	359.34345	259777.6	2.5978E+14	21290.03	6.351494
322644125	0	1708.398	573.5107	363.0708	294820.9	2.9482E+14	24044.46	2.116298
316480156	0	1610.532	592.2589	366.25585	326094.8	3.2609E+14	24659.91	1.360061
310316094	0	1526.825	608.3543	368.78591	352095.3	3.521E+14	23770.85	1.166945
216129997	0	1753.16	379.85	319.855	29260.07	2.926E+13	3866.032	28.054
233117496	0	1812.864	390.5053	323.68957	35984.91	3.5985E+13	4745.827	39.998
274615832	31.71469	1880.258	414.0699	331.1026	51240.54	5.1241E+13	6202.269	63.524
312901169	95.13056	1810.255	429.8439	338.05493	82756.7	8.2757E+13	9607.534	56.988
320698974	267.5762	1635.095	433.5009	343.70178	114534.2	1.1453E+14	15405.07	33.778
310942612	435.8535	1476.623	430.8554	347.33493	149628.8	1.4963E+14	21595.19	28.509
291049273	709.9594	1363.518	424.585	349.17142	190133.9	1.9013E+14	28366.23	60.037
276707794	1156.449	1280.619	415.4299	349.77779	239875.4	2.3988E+14	36296.04	136.112
261323787	1883.734	1211.112	404.045	349.45018	297032.5	2.9703E+14	43553.5	207.955
244389578	3068.404	1155.015	391.9963	348.55001	366052.7	3.6605E+14	51066.47	209.617
226570798	4998.106	1114.438	380.6867	347.15951	431221.9	4.3122E+14	61611.73	176.198
216129997	0	1753.16	379.85	319.855	29260.07	2.926E+13	3861.915	28.054
233117496	0	1812.864	390.5053	323.68957	35968.52	3.5969E+13	4743.791	41.329
274382410	31.68069	1881.124	413.9484	331.10772	51126.21	5.1126E+13	6211.32	64.994
315811043	41.84239	1855.488	434.8058	338.36295	82718	8.2718E+13	8218.418	53.36
345656412	52.00433	1746.234	449.9244	345.01008	115650.1	1.1565E+14	10848.66	27.736
360684725	84.70958	1606.051	458.165	350.35926	152349.2	1.5235E+14	15167.44	21.779
360853169	137.983	1505.438	459.9349	354.36652	194035.5	1.9404E+14	20526.9	47.155
357231064	224.7597	1444.547	456.4663	357.27174	244657.6	2.4466E+14	27822.45	103.425
346840839	366.1099	1394.917	448.5629	358.88701	302949.5	3.0295E+14	36541.3	151.521
331033308	596.3545	1335.874	438.7988	359.36443	373619.8	3.7362E+14	48156.67	160.496
314039960	971.3986	1275.33	429.0485	359.03906	442937.8	4.4294E+14	62843.83	148.622
216129997	0	1753.16	379.85	319.855	29260.07	2.926E+13	3861.915	28.054
233117496	0	1812.864	390.5053	323.68957	35960.02	3.596E+13	4743.789	41.329
275496712	21.63314	1884.083	414.4386	331.13802	51114.38	5.1114E+13	6192.776	64.964
317292079	20.10046	1890.372	439.2827	338.57833	82767.6	8.2768E+13	7511.445	51.62
350854242	18.56781	1823.353	463.0454	345.72261	115945.3	1.1595E+14	10112.83	26.643
374643895	30.24501	1697.128	483.2405	351.98161	153094.2	1.5309E+14	13602.65	34.703
386990181	49.26593	1589.186	497.4908	357.16312	195123.4	1.9512E+14	18455.56	54.162

392618685	80.249	1526.255	504.2789	361.32583	246434.5	2.4643E+14	23212.07	90.37
392091973	130.7172	1489.05	504.7783	364.17981	305485.3	3.0549E+14	28911.27	116.217
381399373	212.9245	1455.54	500.7113	365.74437	376695.2	3.767E+14	38544.97	134.479
365387690	346.8316	1414.785	494.1501	366.467	447772.1	4.4777E+14	49805.42	153.465
216129997	0	1753.16	379.85	319.855	29260.07	2.926E+13	3861.915	28.054
233117496	0	1812.864	390.5053	323.68957	35957.38	3.5957E+13	4743.784	41.329
275839085	17.74189	1886.886	414.723	331.15308	51111.88	5.1112E+13	6135.799	64.906
317729577	12.65402	1904.956	440.9205	338.65501	82756.4	8.2756E+13	7514.178	51.225
352634669	7.56615	1874.503	468.5304	346.00617	116027.2	1.1603E+14	9811.851	18.232
380686753	12.32447	1789.139	496.0661	352.7215	153329.3	1.5333E+14	12781.51	10.977
399023954	20.07526	1685.763	521.3235	358.63911	195635.7	1.9564E+14	17148.89	17.589
409914104	32.70048	1612.579	542.5851	363.72682	247252.8	2.4725E+14	21999.79	29.181
414819298	53.26563	1564.646	558.1323	367.55064	306723.9	3.0672E+14	26179.14	57.197
411139333	86.7641	1529.2	565.6875	370.03535	378385.4	3.7839E+14	31982.53	89.57
401639483	141.3296	1506.556	566.8592	371.52198	450110.5	4.5011E+14	39926.63	117.91
216129997	0	1753.16	379.85	319.855	29260.07	2.926E+13	3861.915	28.054
233117496	0	1812.864	390.5053	323.68957	35955.99	3.5956E+13	4743.775	41.329
276120344	15.47938	1890.3	414.7737	331.17027	51108.16	5.1108E+13	6130.903	64.921
318008551	8.46162	1927.638	441.8382	338.7274	82723.1	8.2723E+13	7448.995	51.194
354213554	1.44383	1948.519	472.5694	346.23655	116038.7	1.1604E+14	9540.811	27.501
383735171	2.35185	1928.786	506.9615	353.30509	153422.4	1.5342E+14	12205.32	51.415
406764622	3.83092	1874.066	544.0904	359.82147	195810.1	1.9581E+14	16207.55	55.807
422765346	6.24016	1817.103	582.678	365.81451	247571.6	2.4757E+14	21073.49	65.489
432640242	10.16456	1755.77	622.368	370.9661	307438.4	3.0744E+14	25593.41	124.397
437128597	16.557	1692.872	663.0393	375.34096	379774	3.7977E+14	30169.65	162.429
435639161	26.9696	1631.38	704.272	379.21409	452128.5	4.5213E+14	34356.03	224.521
216129997	0	1753.16	379.85	319.855	29260.07	2.926E+13	3861.914	28.054
233117496	0	1812.864	390.5053	323.68957	35949.84	3.595E+13	4744.362	41.329
276592208	0	1898.442	414.7085	331.20346	51099.36	5.1099E+13	6107.277	64.807
318148911	0	1951.761	442.0015	338.96954	82715.8	8.2716E+13	7369.049	51.158
354609433	0	1995.014	474.0147	346.98686	116057.1	1.1606E+14	9344.282	31.535
384838091	0	2022.441	511.3055	354.93155	153434.1	1.5343E+14	11723.14	61.244
409034748	0	2046.626	553.6277	362.71977	195843.8	1.9584E+14	15379.52	58.658
426433917	0	2070.316	600.7577	370.34052	247576.3	2.4758E+14	19987.46	69.37
439297009	0	2081.128	655.1408	377.75383	307536.2	3.0754E+14	23372.61	123.832
447270075	0	2076.744	718.6013	385.17079	379937.4	3.7994E+14	27358.87	167.982
451089114	0	2053.971	789.8492	392.735	452564.8	4.5256E+14	32712.35	220.338
246084000	0	1753.16	379.85	319.855	33809.15	3.3809E+13	3509.874	61.511
270010500	2.4627	1812.864	390.5053	323.68957	37621.01	3.7621E+13	3963.362	61.4859
317845300	15.5657	1947.572	417.0736	331.54097	51123.02	5.1123E+13	4959.581	68.6987
355994500	87.4244	2091.554	447.3265	340.01592	63536.22	6.3536E+13	6067.887	87.2065
381268700	128.3259	2065.384	470.7605	346.96881	70945.76	7.0946E+13	7374.341	380.5091
401796500	184.2533	1884.667	483.42	351.88448	76480	7.648E+13	9163.966	1006.095
419259500	248.1855	1767.598	490.4725	356.89933	80945.33	8.0945E+13	11114.65	1488.789
434614600	409.54	1722.833	492.7602	361.86602	85128.07	8.5128E+13	13831.87	2247.692
449019900	626.8813	1697.964	490.7222	366.56202	88788.92	8.8789E+13	16853.51	2742.318
461911900	883.3675	1686.443	485.8113	371.04304	92315.26	9.2315E+13	20267.65	3162.051

473973200	1167.677	1683.682	479.1328	375.35505	96607.06	9.6607E+13	23927.29	3477.71
246084000	0	1753.16	379.85	319.855	33809.15	3.3809E+13	3509.874	61.511
270010500	2.4627	1812.864	390.5053	323.68957	37621.01	3.7621E+13	3963.362	61.4859
317845300	15.5724	1947.549	417.0741	331.54097	51123.02	5.1123E+13	4959.581	68.6987
356197800	23.4267	2101.869	448.4431	340.19197	63700.27	6.37E+13	6129.82	79.9146
383253300	40.6628	2104.731	477.9609	347.92203	72119.12	7.2119E+13	6937.65	223.0096
405031800	64.5764	1978.413	501.4905	354.08111	78110.31	7.811E+13	8018.881	721.3256
422248000	120.9541	1891.902	517.6443	360.10596	82321.25	8.2321E+13	9859.132	1487.574
439808400	160.1478	1858.469	527.0577	365.97883	87159.24	8.7159E+13	11174.05	1733.021
456706400	212.896	1861.385	533.9179	371.89534	91768.47	9.1768E+13	12916.25	2087.833
471661200	297.6163	1871.741	538.5743	377.71958	96084.15	9.6084E+13	15252.8	2475.149
484256100	446.9148	1872.287	540.1797	383.24781	100482	1.0048E+14	18324.63	2945.424
246084000	0	1753.16	379.85	319.855	33809.15	3.3809E+13	3509.874	61.511
270010500	2.4627	1812.864	390.5053	323.68957	37621.01	3.7621E+13	3963.362	61.4859
317845300	15.5806	1947.541	417.0743	331.54097	51123.02	5.1123E+13	4959.581	68.6987
356208900	19.8577	2103.183	448.5531	340.21418	63709.74	6.371E+13	6144.141	79.1864
383866700	19.9509	2143.032	480.627	348.42214	72494.86	7.2495E+13	7012.652	200.8666
406531800	28.588	2074.852	511.4254	355.60202	78984.87	7.8985E+13	7947.629	596.0419
426101500	28.588	2060.36	542.9487	363.05868	84404.11	8.4404E+13	8835.031	1036.437
444496000	41.052	2087.458	573.5018	370.72911	89674.62	8.9675E+13	9718.766	1546.525
462349700	57.4871	2110.954	599.9446	378.28435	94527.96	9.4528E+13	10912.8	1872.692
479432700	68.734	2143.896	623.1286	385.83276	99638.89	9.9639E+13	12354.12	2141.931
495667000	82.7129	2185.218	645.0564	393.44522	105504	1.055E+14	14109.11	2547.411
246084000		1753.16	379.85	319.855	33809.15	3.3809E+13	3509.874	61.511
270004500		1812.864	390.5053	323.68957	37619.94	3.762E+13	3958.756	61.4885
317867200		1958.352	417.8888	331.73189	51141.04	5.1141E+13	4997.764	68.3768
356336400		2136.883	451.9973	340.94348	63820.12	6.382E+13	6151.372	77.3847
384612200		2314.385	491.2553	350.99258	73023.94	7.3024E+13	7270.561	96.2335
408098000		2478.77	535.2207	361.56127	79955.97	7.9956E+13	8559.191	142.8895
428164000		2634.316	583.6923	372.57319	85600.53	8.5601E+13	9573.995	206.1249
447496900		2785.519	636.942	384.04251	91401.29	9.1401E+13	10537.99	292.5306
466442000		2936.525	695.6742	395.9181	96993.27	9.6993E+13	11555.6	378.8032
484770400		3087.259	760.9923	408.1424	102821	1.0282E+14	12614.94	441.1172
502721500		3238.033	834.3412	420.66149	109425	1.0943E+14	13777.87	524.289
177627720								
193120126	0	1812.864	390.5053	323.68957			4144.848	30.33453
226782499	0	1921.036	415.2453	331.16247			4956.901	54.48332
249935026	69.90315	1940.883	433.1226	338.29319			7028.708	199.7464
268141071	113.8651	1926.957	440.3508	345.23687			9166.479	351.7711
282535985	185.4743	1947.835	444.1231	352.66659			11391.09	542.4349
287181247	302.118	1963.588	445.2066	360.51557			13354.96	728.6418
286189684	492.118	1964.091	442.356	368.70911			15198.07	893.285
280744657	801.6094	1937.045	433.2123	376.95326			16549.98	1062.837
270100951	1305.737	1889.896	417.6145	384.75886			17760.8	1324.284
257931574	2126.906	1841.637	397.1594	391.96667			18831.28	2204.843
177627720								
193120126	0	1812.864	390.5053	323.68957			4144.848	30.33455

226782499	0	1921.036	415.2453	331.16247			4956.901	54.4833
251364608	34.6142	1959.573	438.4117	338.47259			6518.121	110.0375
271523958	56.38304	1970.224	455.5431	345.72203			8319.422	187.9401
288599695	91.84176	1997.525	466.391	353.27912			10221.17	302.1048
295633934	149.6004	2016.221	472.5781	361.08338			12091.92	439.8529
297222474	243.6834	2027.33	476.0988	369.12603			13951.78	615.4754
293815594	396.9357	2017.851	475.603	377.4044			15396.86	777.819
284751538	646.5664	1984.089	468.5495	385.73505			16603.51	925.6869
273645188	1053.186	1935.698	454.8193	393.68536			17731.03	1152.563
177627720								
193120126	0	1812.864	390.5053	323.68957			4144.848	30.33455
226782499	0	1921.036	415.2453	331.16247			4956.901	54.4833
252019242	20.34388	1974.549	440.5192	338.64818			6370.159	95.63851
273209686	33.13803	2005.847	463.4998	346.25932			7935.955	145.885
291830163	53.97845	2043.44	481.6414	354.10516			9569.76	208.0479
300215009	87.92494	2063.284	493.5641	362.05714			11272.62	288.2907
303465522	143.2207	2071.441	500.919	370.07464			13020.66	415.6971
307520497	147.267	2073.759	505.1717	378.27386			13587.94	451.2379
306897898	157.5793	2080.462	508.5128	386.62144			14078.32	489.8371
303384299	201.0655	2089.317	511.8824	394.97277			14880.55	560.0934
177627720								
193120126	0	1812.864	390.5053	323.68957			4144.848	30.33455
226782499	0	1921.036	415.2453	331.16247			4956.901	54.4833
252974249	2.114418	2038.132	443.7189	339.5447			6335.965	84.77068
275974756	3.444164	2159.899	475.6372	349.23327			7604.555	117.7359
297648599	5.610189	2245.016	508.4056	359.19614			8721.818	146.8847
309142476	9.138373	2293.199	540.5294	369.02267			9808.207	170.6041
316252984	14.88548	2314.926	571.1252	378.45966			10828.11	188.9121
319765569	24.24685	2307.729	597.5109	387.34773			11729.7	195.8065
318058340	39.4956	2280.985	617.5458	395.72455			12594.73	193.9123
314795554	64.33409	2249.813	631.4741	403.76233			13500.73	190.5601
177627720	0	1753.16	379.85	319.855			3733.243	20.20767
193120126	0	1812.864	390.5053	323.68957			4144.848	30.33455
226806023	0	1945.321	415.996	331.53214			5044.324	51.8459
253093463	0	2117.301	446.6259	340.42382			6396.628	82.34672
276367922	0	2304.988	482.375	350.4322			7647.878	112.0634
298845781	0	2451.961	520.9601	361.25518			8731.882	137.1466
310854798	0	2554.269	561.3776	372.62274			9722.47	157.7131
319025194	0	2632.626	602.9313	384.30634			10591.25	176.4068
324128626	0	2671.109	643.1318	396.20072			11257.65	184.6751
324630715	0	2675.739	681.1994	408.17059			11766.1	182.7066
324481161	0	2668.365	718.3727	420.18297			12184.82	169.1904
205757600	0	1753.16	379.85	319.855	29680	2.968E+13	3557	23.92
235413800	0	1812.864	390.5053	323.68957	32950	3.295E+13	4176	34.61
303699700	7.333	1904.271	414.9077	331.13662	47109.47	4.7109E+13	5795	45.62
382277900	96.32	1822.309	439.2346	337.69586	69285.84	6.9286E+13	7042	78.22
463265700	348.8	1617.625	454.8986	343.5938	100751.7	1.0075E+14	11450	310.1

520819300	628.6	1475.146	453.7367	350.82057	138836.7	1.3884E+14	21640	457.8
555408400	1204	1386.759	438.6597	358.63934	184923.2	1.8492E+14	34490	535.8
572768000	1724	1335.886	419.4862	365.31553	223917.6	2.2392E+14	47900	626.4
573378800	2904	1300.28	401.9195	371.12852	285116.2	2.8512E+14	62360	721.3
558313300	4681	1264.49	385.7025	376.29198	342716.6	3.4272E+14	76770	759.8
526916100	7464	1222.31	370.1514	380.3818	402916.9	4.0292E+14	87410	755.9
205757500	0	1753.16	379.85	319.855	29680	2.968E+13	3557	23.92
235444900	0	1812.864	390.5053	323.68957	32950	3.295E+13	4176	34.61
304184700	7.333	1904.687	414.8545	331.11989	47109.47	4.7109E+13	5795	45.62
382473000	41.95	1881.677	441.7258	338.0393	70400.51	7.0401E+13	7603	68.05
460410300	143.3	1741.925	467.4384	343.84257	105659.5	1.0566E+14	10100	118.1
515365200	258.4	1601.803	484.0805	349.08025	147340.1	1.4734E+14	15600	110.9
548486200	493.1	1507.179	486.7812	355.04402	194126.2	1.9413E+14	25070	101.9
566200900	704.8	1434.51	477.7632	361.60235	234018	2.3402E+14	37390	114.4
569582500	1193	1365.116	463.0492	367.55417	296318.5	2.9632E+14	52730	184.2
557599900	1938	1295.545	445.6751	372.73883	353321	3.5332E+14	70400	416.5
530170700	3106	1237.088	427.6169	377.31904	413219.6	4.1322E+14	83230	604.6
205757500	0	1753.16	379.85	319.855	29680	2.968E+13	3557	23.92
235444900	0	1812.864	390.5053	323.68957	32950	3.295E+13	4176	34.61
304184700	7.333	1904.7	414.8492	331.11989	47109.47	4.7109E+13	5795	45.62
386507800	23.59	1930.817	442.3492	338.19333	70515.71	7.0516E+13	7844	61.1
460248100	72.53	1857.46	471.4091	344.43327	106576	1.0658E+14	10060	94.89
514826600	131.4	1730.107	496.6991	349.22238	149949.3	1.4995E+14	13840	108.7
546835200	251.7	1615.035	514.7885	352.94863	198225.1	1.9823E+14	20640	93.46
562247800	359.5	1525.964	522.9733	357.10367	238718.4	2.3872E+14	30450	76.8
563882300	607.1	1443.366	520.2652	361.80904	301715.2	3.0172E+14	44230	83.6
551415000	980.8	1358.624	508.3498	366.72618	360220.3	3.6022E+14	61050	208.5
526742700	1570	1278.011	491.476	371.19061	420621.6	4.2062E+14	74990	370.2
205757500	0	1753.16	379.85	319.855	29680	2.968E+13	3557	23.92
235444900	0	1812.864	390.5053	323.68957	32950	3.295E+13	4176	34.61
304184700	7.333	1904.698	414.8458	331.11989	47109.47	4.7109E+13	5795	45.62
386503200	22.29	1933.404	442.5619	338.2332	70566.16	7.0566E+13	7879	69.29
466501500	56.71	1891.892	473.0421	344.67055	106879.8	1.0688E+14	10100	151.1
514563500	92.38	1792.092	502.3879	349.95626	150964.1	1.5096E+14	13380	244.1
546391600	150.5	1673.229	527.4181	353.98335	200536.6	2.0054E+14	18220	252.5
561872000	215.6	1586.78	546.0745	357.56503	242421.1	2.4242E+14	25580	223
561299700	280.8	1518.442	559.1474	360.97849	307817.1	3.0782E+14	35910	153.3
546428900	345.9	1444.797	567.6406	363.92471	369218.9	3.6922E+14	47540	72.64
519190000	411.1	1361.71	573.7102	366.05058	432820.7	4.3282E+14	55870	38.1
205757500	0	1753.16	379.85	319.855	29680	2.968E+13	3557	23.92
235444900	0	1812.864	390.5053	323.68957	32950	3.295E+13	4176	34.61
304184700	7.333	1904.691	414.8542	331.11989	47109.47	4.7109E+13	5795	45.62
386616700	11.72	1970.243	443.9563	338.41985	70638.24	7.0638E+13	7982	60.64
467425800	22.27	2017.185	479.7991	345.45721	107493.4	1.0749E+14	10330	106.7
521808800	36.28	2017.896	520.1116	351.56325	152483.9	1.5248E+14	13130	221.3
556845100	59.1	1950.076	562.3711	356.30627	203070.1	2.0307E+14	16350	387.1
570324700	84.68	1829.418	603.3297	360.09284	245660.7	2.4566E+14	21310	519.2

560996900	110.3	1679.353	640.6846	363.03054	311550.5	3.1155E+14	29390	569.5
545549300	135.9	1541.429	673.4373	365.0222	372638.7	3.7264E+14	39870	553.4
517856900	161.4	1432.861	702.3926	365.88887	436331.5	4.3633E+14	48250	558.4
205757600	0	1753.16	379.85	319.855	29680	2.968E+13	3557	23.92
235413800	0	1812.864	390.5053	323.68957	32950	3.295E+13	4176	34.61
304241300	0	1927.944	417.2487	331.86119	47100	4.71E+13	5814	44.09
385223300	0	2077.052	452.7668	341.05774	70600	7.06E+13	7741	56.02
465109600	0	2305.153	499.6782	350.48212	107700	1.077E+14	10130	92.08
517348100	0	2565.794	559.6919	359.40246	153300	1.533E+14	12780	160.9
545685900	0	2748.008	635.7926	367.47058	204900	2.049E+14	15430	247.9
559745300	0	2821.259	730.0255	374.95656	248400	2.484E+14	18340	352.5
558366700	0	2807.665	841.5202	381.75309	315400	3.154E+14	22280	466.6
543481600	0	2721.972	963.8416	387.79905	376900	3.769E+14	28220	564.8
516273100	0	2598.51	1088.97	392.83192	439900	4.399E+14	35130	638.5

Coal capacity	Concentrated solar capacity	Gas capacity	Geothermal capacity	Hydropower capacity	Nuclear capacity	Offshore wind capacity	Oil capacity	Onshore wind capacity	Other electricity capacity
967.1142	0.408451	1011.006		871.2293	403.097	0.6842	405.4771	58.03196	9.507541
1139.278	1.256	1170.674		1028.111	422.7627	3.1927	434.5956	193.142	11.24127
1089.114	8.269087	1616.254		1314.283	452.0645	19.43807	325.0383	470.4211	16.97595
871.7687	18.59721	1469.245		1430.762	452.4573	51.14825	248.7839	476.0843	27.49336
254.4913	577.3639	1072.343		1729.524	372.9538	467.2583	31.34222	1022.322	87.54459
209.9185	1978.521	1551.947		1820.346	213.9031	900.5343	8.938429	1986.75	136.447
268.0568	3690.9	2139.423		1876.622	184.2755	877.3956	7.83784	2112.915	181.4908
346.0633	5178.58	2639.027		1936	185.4034	655.3264	8.124931	1643.717	225.5976
336.2973	5959.577	2657.411		1990.567	236.2574	777.0181	7.283624	1608.656	270.6856
282.6755	6356.646	2253.057		2050.245	304.9577	930.3728	6.159712	1890.414	316.622
192.8441	6203.701	1886.382		2077.708	305.6004	776.3416	4.787603	1790.889	360.1929
967.1142	0.408451	1011.006		871.2293	403.097	0.6842	405.4771	58.03196	9.507541
1145.203	1.256	1167.242		1028.111	422.7627	3.1927	434.7843	193.142	11.24127
1358.195	6.389296	1672.53		1341.036	448.1711	19.43218	332.0894	445.4367	18.18246
1331.024	72.76783	2399.909		1576.637	453.498	187.5738	259.5569	647.1627	46.37654
1204.439	498.1575	2752.862		1751.807	347.1891	539.5996	136.7585	861.1098	90.33232
921.2822	1814.396	3040.355		1819.31	172.8064	766.6543	13.29367	1383.281	136.3408
741.3165	3648.462	3017.214		1878.782	129.6688	728.8048	3.984897	1987.364	181.4908
878.2613	5434.34	2847.3		1937.316	107.402	781.8494	3.345448	2109.278	226.356
891.9902	6388.975	2601.152		1987.437	117.5619	960.0585	2.673737	1859.289	271.547
806.116	6350.846	2354.686		2035.21	129.6582	907.529	0.981908	1539.682	316.0923
591.6446	7605.267	2397.229		2082.507	143.3619	818.3722	0.854149	1746.18	359.2863
967.1142	0.408451	1011.006		871.2293	403.097	0.6842	405.4771	58.03196	9.507541
1146.435	1.256	1166.455		1028.111	422.7627	3.1927	434.8128	193.142	11.24127
1421.552	5.790864	1683.2		1345.819	447.8269	17.94565	333.4576	444.6097	18.47044
1641.942	31.20054	2612.443		1577.071	442.6673	132.1734	260.0466	634.9364	46.37866
1744.23	198.3817	3375.869		1761.819	318.1085	510.4467	143.0688	886.0544	91.35909
1657.212	839.5912	4099.308		1820.837	140.3747	883.5641	37.39004	1428.04	136.447
1471.734	2455.441	4406.71		1878.782	92.9352	922.4809	11.79861	1732.065	181.4908
1431.351	4782.221	4116.567		1938.363	62.08425	905.1321	4.967896	2153.686	226.5345
1333.285	6509.652	3517.23		1993.917	44.93508	1064.435	2.994906	2328.328	271.3307
1142.411	6642.047	2817.367		2054.18	52.49417	1088.671	1.132294	2101.093	316.612
898.6857	6850.805	2491.775		2102.164	63.37466	953.7917	0.612264	2003.075	361.3211
967.1142	0.408451	1011.006		871.2293	403.097	0.6842	405.4771	58.03196	9.507541
1146.605	1.256	1166.355		1028.111	422.7627	3.1927	434.815	193.142	11.24127
1425.103	5.724216	1689.812		1345.791	447.8122	17.72753	333.5298	444.3717	18.46897
1736.052	25.62778	2611.211		1577.071	441.2135	117.1069	257.7094	624.5008	46.37866

2111.587	124.8312	3484.248		1762.228	311.5723	457.749	138.3481	857.6037	91.40331
2393.073	392.068	4286.645		1820.837	128.0851	834.1014	38.99168	1360.553	136.447
2516.338	1080.582	4807.685		1878.782	76.89836	935.0019	13.57557	1644.444	181.4908
2391.468	3044.718	4848.693		1938.363	39.39815	919.9186	5.80416	1848.747	226.5345
2061.766	5314.862	4533.64		1997.33	16.88613	1020.423	2.90736	2200.557	271.5308
1723.058	6391.279	4181.814		2057.524	22.32142	1144.029	1.453064	2394.093	316.622
1214.296	6688.285	4036.84		2117.105	23.41139	1026.929	0.728066	2376.649	361.6658
967.1142	0.408451	1011.006		871.2293	403.097	0.6842	405.4771	58.03196	9.507541
1146.618	1.256	1166.347		1028.111	422.7627	3.1927	434.8152	193.142	11.24127
1426.399	5.700469	1689.515		1346.035	447.812	17.63592	333.5559	444.2523	18.48137
1757.47	24.32383	2608.681		1577.071	441.0693	112.6597	256.8643	621.1443	46.37866
2208.786	111.5134	3511.657		1762.228	310.2281	439.85	132.2743	855.3053	91.40331
2571.693	328.4404	4310.247		1820.837	126.0087	809.5539	39.43519	1340.192	136.447
2912.966	773.2396	4857.325		1878.782	73.89302	910.8605	13.82658	1591.858	181.4908
3194.92	2013.003	5031.552		1938.363	34.46153	887.9611	5.743623	1777.796	226.5345
3227.006	3982.155	4950.68		1997.943	9.460465	943.8033	2.562412	2044.96	271.5783
3015.137	5309.353	4790.264		2057.524	8.444734	886.9701	1.149439	2195.256	316.622
2533.823	5646.774	4749.764		2117.105	5.751502	752.1234	0.522635	2267.013	361.6658
1208.495	0.3	891.075	9.764	855.358	405.859	0	408.377	55.351	
1553.732	1.731	1065.488	16.075	1127.523	415.13	0	233.178	254.922	
1613.275	1.731	1774.296	14.721	1225.253	510.583	0	87.756	653.669	
1175.07	12.206	2133.945	36.193	1634.296	762.768	73.833	45.119	2108.952	
477.651	56.152	2605.065	112.055	2123.571	1248.415	292.998	18.577	4425.197	
103.439	153.781	2538.66	167.891	2341.763	2243.648	647.958	10.681	6072.239	
38.937	341.217	2270.977	219.476	2555.453	3658.643	868.073	10.285	7724.418	
15.657	658.858	1573.546	270.27	2680.816	4459.27	1183.026	0.645	10058.44	
5.265	1119.525	1480.223	278.07	2749.172	4604.702	1519.714	0.001	12830.54	
1.24	1760.21	1502.834	287.276	2795.207	4151.388	2332.063	0.001	15122.17	
0.03	2706.043	1792.994	295.515	2825.668	3285.822	3479.677	0	17783.77	
1208.581	0.3	886.675	9.761	855.159	405.859	0	408.458	55.668	
1551.226	1.731	1064.809	16.072	1127.334	415.13	0	232.871	255.239	
1615.484	1.731	1773.927	14.718	1225.067	517.699	0	87.774	652.475	
1146.576	1.581	2861.203	8.783	1467.604	705.903	14.726	45.109	1542.215	
481.693	0	4214.792	14.761	1637.852	995.004	82.783	18.924	2433.376	
158.12	11.44	5277.666	25.741	2010.801	1616.659	153.766	10.703	3528.955	
151.718	49.886	5588.482	39.126	2220.299	2527.999	160.448	10.285	4913.721	
140.467	140.368	5506.158	68.915	2460.321	3549.061	194.403	0.645	6696.389	
93.673	309.329	4655.599	143.09	2645.272	4178.811	474.502	0.001	9812.325	
78.942	604.81	4267.885	218.133	2788.212	4476.083	996.11	0.001	14154.4	
65.34	1076.35	3711.095	284.64	2826.235	4275.281	2427.28	0	18583.07	
1208.581	0.3	886.675	9.761	855.159	405.859	0	408.458	55.668	
1551.259	1.731	1064.776	16.072	1127.331	415.13	0	232.871	255.239	
1614.296	1.731	1766.62	14.718	1219.116	517.692	0	87.774	648.413	
1173.583	1.581	2896.461	8.783	1316.548	515.831	0	45.109	1210.556	
486.978	0	4712.235	1.462	1616.08	595.585	0	18.924	2127.393	
124.407	0	6240.346	9.754	1733.223	898.287	0	10.704	3282.19	
120.289	0	7168.648	20.5	2042.709	1612.955	17.357	10.285	4521.637	

122.55	4.176	6780.278	33.588	2250.893	2848.424	26.941	0.645	5616.395
139.529	30.241	6860.963	58.393	2427.428	3953.613	80.617	0.001	6965.821
122.709	99.561	6652.435	103.285	2659.684	4638.2	254.855	0.001	10087.95
131.67	234.498	6221.054	187.828	2775.967	5133.383	715.742	0	14373.04
1208.581	0.3	886.675	9.761	855.159	405.859	0	408.458	55.668
1551.258	1.731	1064.78	16.072	1127.322	415.13	0	232.871	255.239
1615.257	1.731	1770.619	14.718	1219.107	517.672	0	87.774	586.564
1203.969	1.581	2957.59	8.392	1299.642	482.919	0	45.109	1197.518
660.908	0	4773.125	1.044	1569.448	453.548	0	18.924	1937.532
443.021	0	6415.364	1.044	1654.466	642.994	0	10.704	2900.356
361.409	0	8169.03	0.625	1757.112	1019.553	0	10.285	4336.712
209.818	0	9245.938	0.625	1913.975	1870.821	0	0.645	5505.533
66.886	0	8678.841	3.676	2219.417	3231.544	6.331	0.001	6338.78
106.755	5.911	6851.948	26.463	2551.319	4973.72	57.813	0.001	7312.789
162.155	21.012	7023.52	58.106	2651.798	5907.931	220.077	0	9773.232
1208.581	0.3	886.675	9.761	855.159	405.859	0	408.459	55.668
1551.244	1.731	1064.785	16.072	1127.322	415.13	0	232.871	255.239
1622.503	1.731	1785.881	14.718	1203.07	515.824	0	87.774	577.031
1305.72	1.581	2979.112	7.569	1285.545	443.409	0	45.109	1070.444
998.938	0	4738.963	0.552	1545.23	300.53	0	18.924	1627.025
1003.563	0	6410.777	0.552	1602.527	243.48	0	10.704	2537.575
1171.917	0	8364.108	0.33	1679.026	408.626	0	10.285	3798.951
1221.924	0	10508.69	0.198	1744.525	738.856	0	0.645	5229.015
932.452	0	11566.39	0.198	1808.327	1441.858	0	0.001	6584.746
613.012	0	12313.31	0.198	1880.185	2236.559	0	0.001	7574.665
180.631	3.6	12352.25	0.118	2461.538	3639.268	35.062	0	7932.377
1208.573	0.3	886.682	9.761	855.159	405.859	0	408.459	55.668
1551.261	1.731	1065.357	16.072	1127.322	415.13	0	232.871	255.239
1633.631	1.731	1776.817	14.718	1219.093	510.503	1.397	87.775	539.355
1400.377	1.581	2938.788	7.348	1299.642	437.005	1.397	45.109	930.896
1246.33	0	4651.492	0	1449.456	280.877	1.397	18.924	1417.627
1401.864	0	6273.41	0	1496.386	164.578	1.397	10.704	2120.488
1793.776	0	8174.206	0	1559.967	216.564	1.397	10.285	3132.977
2188.913	0	10345.67	0	1660.99	379.041	1.397	0.645	4360.887
2618.646	0	11573.9	0	1771.369	670.335	0	0.001	5090.801
2695.971	0	12595.77	0	1830.528	1171.696	0	0.001	6253.277
2397.212	0	14291.69	0	1847.502	1765.228	17.531	0	7932.747
1336.707		604.4403	8.7966	826.382	446.4509		188.9644	35.3325
1558.797		661.1185	9.1906	947.0204	457.5221		213.0637	43.2872
1906.579		786.1355	10.8795	1217.501	573.113		263.429	106.4602
1866.045		897.294	12.5576	1499.603	853.5622		282.1999	434.5027
1086.447		867.5611	14.4541	2028.14	971.7501		327.0354	1107.792
1120.694		819.178	16.071	2157.197	827.6001		312.2426	1674.147
1293.82		802.2418	17.4926	2234.432	662.012		293.2141	2486.241
1045.381		731.62	18.8817	2443.697	633.5754		266.1866	3793.876
853.6205		659.7239	20.2102	2520.373	635.6717		245.1536	5281.18
684.5843		551.9451	21.5337	2520.373	626.3032		211.284	7135.913

542.5672	456.8641	22.9643	2520.373	602.2237	176.7628	9049.08
1336.707	604.4403	8.7966	826.382	446.4509	188.9644	35.3325
1558.797	661.1185	9.1906	947.0204	457.5221	213.0637	43.2872
1906.579	786.1355	10.8795	1217.501	573.113	263.429	106.4602
2133.929	854.0991	12.351	1498.876	851.9775	284.6063	311.8137
1655.461	879.0911	13.9336	1886.333	951.9803	335.1781	657.2819
1431.409	772.7874	15.5165	2097.747	884.3293	294.7325	1054.178
1398.621	666.0965	16.928	2243.608	796.7804	242.9729	1730
1424.974	675.7736	18.3115	2349.351	690.3162	245.9421	2341.542
1461.077	671.9053	19.6445	2424.754	627.5396	248.9704	3163.73
1415.127	651.6144	20.9754	2485.822	592.1114	248.8693	4336.894
1238.569	606.2031	22.4136	2520.373	598.9519	241.2031	5902.378
1336.707	604.4403	8.7966	826.382	446.4509	188.9644	35.3325
1558.797	661.1185	9.1906	947.0204	457.5221	213.0637	43.2872
1906.579	786.1355	10.8795	1217.501	573.113	263.429	106.4602
2162.3	850.3594	12.297	1498.826	851.8702	284.4476	304.5432
2068.143	880.905	13.6695	1772.887	900.4445	329.1332	563.8515
2029.085	853.2133	15.1108	1979.838	761.259	317.9447	821.7309
2133.272	783.5704	16.4944	2037.209	596.7124	281.2418	1127.665
1867.118	695.7149	17.8686	2184.176	527.3379	257.9778	1516.401
1854.448	612.0258	19.2029	2282.791	479.7949	234.1682	2060.77
2093.876	571.7496	20.5408	2334.624	411.532	225.8197	2656.928
2332.247	539.2225	21.9881	2354.653	360.799	215.9976	3387.528
1336.707	604.4403	8.7966	826.382	446.4509	188.9644	35.3325
1571	661.892	9.194	937.6342	449.3162	213.0396	43.4013
2110.059	783.6254	10.9682	1159.794	524.5556	263.8251	57.1599
2791.207	940.2569	12.7537	1316.08	592.5745	312.7029	75.2413
3496.536	1052.656	14.5341	1528.463	575.1862	357.2171	95.8726
4309.221	1165.433	16.1714	1859.332	494.9324	375.3293	114.2928
5048.089	1188.251	17.6472	2076.555	409.7721	365.6244	153.5991
5868.657	1147.202	19.0954	2159.64	342.2928	368.849	200.2114
6715.017	1096.278	20.5016	2237.118	283.2221	368.2831	269.4603
7610.444	1049.907	21.9155	2283.161	236.0092	381.2876	349.4753
8586.262	1005.416	23.4492	2296.368	206.137	375.2147	450.7418

1225.958	841.2101	9.716098	349.6053	1085.217	0
1693.754	1140.513	67.0341	510.8682	360.6318	0
1228.808	1243.012	166.622	1530.018	253.1453	0
1073.495	1254.237	204.1142	2413.031	129.1626	0
1071.386	1216.835	223.4281	3153.946	68.90377	0
931.6911	1224.682	231.3622	3905.114	49.13613	0
628.7336	1106.922	233.9821	4587.919	49.56565	0
233.7913	801.3357	231.6631	5183.68	67.5284	0
50.59647	458.0889	230.0954	5109.573	99.44499	0
8.568845	148.5998	180.6275	4893.532	63.78672	0
1225.958	841.2101	9.716106	349.6053	1085.217	0

1693.754	1140.513	67.0341	510.8682	360.6322	0
1716.053	1293.324	139.5919	1008.812	305.8904	0
1345.413	1369.899	182.9874	1846.324	202.3471	0
1006.978	1318.441	207.8897	2701.807	121.6	0
920.5796	1135.353	220.7376	3367.095	77.61129	0
804.8737	1023.967	222.8477	4024.203	49.01813	0
633.9834	937.3923	217.0962	4541.143	44.37575	0
302.3548	720.81	210.888	4839.151	53.88509	0
74.31952	442.4846	199.5887	4794.77	77.12468	0
1225.958	841.2101	9.716106	349.6053	1085.217	0
1693.754	1140.513	67.0341	510.8682	360.6322	0
1846.253	1331.803	128.3021	853.4231	328.418	0
1737.86	1426.401	165.1665	1432.186	230.208	0
1325.98	1432.084	190.7936	2202.566	155.2775	0
934.0023	1214.835	210.5004	2947.221	125.6095	0
782.0435	994.6936	217.2496	3598.212	73.38565	0
689.3045	900.2817	198.5876	3875.422	49.57959	0
637.6053	806.0891	181.7046	4024.789	55.17809	0
532.3713	693.9291	171.8699	4050.719	45.52628	0
1225.958	841.2101	9.716106	349.6053	1085.217	0
1693.754	1140.513	67.0341	510.8682	360.6322	0
2014.376	1395.452	115.6949	727.4788	369.4773	0
2139.452	1536.954	141.358	1042.492	272.6893	0
2160.038	1612.299	150.9597	1360.336	199.7782	0
2150.953	1416.25	157.194	1657.732	208.2219	0
2102.007	1218	161.1226	1974.2	176.1341	0
1592.537	1102.254	171.7487	2391.867	173.2052	0
1035.827	978.3102	174.6699	2804.311	170.1273	0
501.7329	848.5339	170.2217	3150.743	129.49	0
1031.966	631.8461	8.304925	351.0846	1239.128	
1225.958	841.2101	9.716106	349.6053	1085.217	
1748.912	1187.257	64.68386	481.8749	432.9278	
2085.85	1435.85	112.3128	698.3523	397.5347	
2239.666	1598.721	136.5254	985.0269	307.3984	
2297.31	1696.712	144.5328	1261.837	232.3134	
2326.558	1527.514	148.3682	1508.224	250.9439	
2349.912	1332.252	147.6353	1750.521	222.5091	
1962.312	1251.47	151.7688	2031.551	234.5549	
1681.387	1175.393	149.1296	2191.384	247.3909	
1453.393	1166.226	141.6507	2238.914	235.0923	
1134	0	925.2	7.727	702.4	400.9
1299	0.53	1147	11.55	743.3	403.7
1297	4.427	2241	14.31	702.1	481.9
650.4	66.08	2761	33.26	890.5	830.6
134.4	684.5	1752	42.76	2105	1627

0.5999	3009	1165	43.19	3539	2295
0.2419	6551	730.5	42.26	4102	2659
0.0664	9700	383.8	40.25	4326	2854
0.0826	12420	150.4	39.48	4515	2809
0.089	15000	84.77	39.3	4683	2662
0.0777	17940	45.36	39.46	4798	2485
1134	0	925.2	7.727	702.4	400.9
1299	0.53	1147	11.55	743.3	403.7
1297	4.427	2241	14.31	702.1	481.9
705.5	12.25	4062	28.5	750.4	681.5
187.1	116.1	4742	38.83	1277	1159
2.116	737	4367	42.28	2403	1894
1.084	2674	3793	43.41	3483	2501
0.601	5964	2841	42.9	4084	2890
0.3086	10050	1375	42.32	4288	3018
0.1041	13850	581.3	41.11	4390	2799
0.0772	16980	302.8	40.33	4475	2500
1134	0	925.2	7.727	702.4	400.9
1299	0.53	1147	11.55	743.3	403.7
1297	4.427	2241	14.31	702.1	481.9
827.5	5.07	4448	27.05	705.6	615.4
329	24.87	6057	36.38	987.6	881.8
103.4	208.9	6566	40.21	1762	1356
41.39	1074	6481	42.27	2745	1920
32.71	3383	5398	43.41	3585	2464
19.61	7306	3399	43.41	4100	2888
7.433	11640	1470	42.89	4277	2935
6.648	15280	826.4	43.41	4354	2645
1134	0	925.2	7.727	702.4	400.9
1299	0.53	1147	11.55	743.3	403.7
1297	4.427	2241	14.31	702.1	481.9
882.8	4.449	4444	26.59	696.8	606.5
484.5	9.686	6128	35.54	929.2	848.6
356.9	79.89	6801	39.47	1598	1307
285.6	485.9	6545	41.62	2448	1880
275.1	1782	5876	43.07	3164	2341
274	4345	4733	43.41	3744	2654
294.4	7587	3308	42.93	4080	2703
366.9	10330	2351	43.41	4209	2492
1134	0	925.2	7.727	702.4	400.9
1299	0.53	1147	11.55	743.3	403.7
1297	4.427	2241	14.31	702.1	481.9
1255	4.25	4364	24.53	663	545.8
1188	4.001	6536	32.5	742.3	632.8
1089	13.13	8096	37.9	1132	880.7
981.1	103	8132	40.75	1866	1396
787.7	477.8	6937	42.44	2537	2178

638.7	1517	5343	43.41	3132	2973
640.7	3668	3864	43.16	3741	3259
638.1	6746	2478	43.41	4214	3012
1134	0	925.2	7.727	702.4	400.9
1299	0.53	1147	11.55	743.3	403.7
1577	4.427	2027	12.73	688.8	480.8
2231	4.25	3415	17.68	610.6	487.5
3262	3.219	5041	23.12	564.3	425.6
4381	1.778	6260	31.25	638.7	348.6
5449	7.336	6718	35.64	956.4	246.4
6210	46.87	6798	38.54	1540	203.6
6476	223.7	6654	40.95	2193	383.1
6202	788.4	6056	42.26	2640	763.2
5519	2056	4878	43.41	3011	1304

Solar capacity	Solar PV capacity	Wind capacity	Black carbon emissions	Methane emissions	Fossil methane emissions	Land methane emissions	Carbon monoxide emissions	CO2 emissions
4.902305	4.493854	58.71616	10166850	3.18E+08		1.54E+08	NaN	33166074220
40.07435	38.81835	196.3347	10420980	3.48E+08		1.64E+08	NaN	35488828780
287.0316	278.7625	489.8592	7281273	3E+08		1.53E+08	NaN	33208799480
404.7742	386.177	527.2326	3990174	2.15E+08		1.23E+08	NaN	17967968260
2934.135	2356.771	1489.58	3308903	1.79E+08		1.06E+08	NaN	6413946208
4996.537	3018.016	2887.284	2538134	1.53E+08		86351827	NaN	968036255
6170.391	2479.491	2990.311	2308984	1.44E+08		82002647	NaN	-1649998545
6299.851	1121.271	2299.043	2174113	1.36E+08		78378320	NaN	-4136923829
7206.669	1247.092	2385.674	2040057	1.26E+08		74407122	NaN	-7370205445
7876.061	1519.415	2820.787	1907362	1.17E+08		70342212	NaN	-10567707520
7878.032	1674.331	2567.231	1797451	1.1E+08		66408749	NaN	-14340424640
4.902305	4.493854	58.71616	10166850	3.18E+08		1.54E+08	NaN	33166074220
40.07435	38.81835	196.3347	10420980	3.48E+08		1.64E+08	NaN	35488821620
254.8332	248.4439	464.8689	7713113	3.15E+08		1.53E+08	NaN	38389781580
659.4355	586.6677	834.7365	4706756	2.57E+08		1.33E+08	NaN	33930925130
2162.961	1664.803	1400.709	3825954	2.2E+08		1.11E+08	NaN	25904736820
4640.146	2825.75	2149.935	3227433	1.9E+08		92485721	NaN	17732934570
6474.691	2826.229	2716.169	2945252	1.75E+08		87122877	NaN	10565807940
7558.562	2124.222	2891.127	2767615	1.57E+08		83303713	NaN	4785242147
8098.997	1710.022	2819.348	2417529	1.35E+08		76434132	NaN	-2921840088
8053.079	1702.233	2447.211	2236856	1.28E+08		72927185	NaN	-8098321208
10154.25	2548.979	2564.552	1934944	1.2E+08		68847568	NaN	-8347350180
4.902305	4.493854	58.71616	10166850	3.18E+08		1.54E+08	NaN	33166074220
40.07435	38.81835	196.3347	10420980	3.48E+08		1.64E+08	NaN	35488818040
254.2848	248.4939	462.5553	7821450	3.54E+08		1.6E+08	NaN	39638793620
566.0787	534.8782	767.1098	4998291	3.09E+08		1.41E+08	NaN	39351400720
1674.526	1476.144	1396.501	4199383	2.69E+08		1.3E+08	NaN	37443119140
4245.226	3405.635	2311.604	3495168	2.39E+08		1.15E+08	NaN	32947266600
6727.268	4271.827	2654.546	3211494	2.15E+08		1.06E+08	NaN	27955583340
8742.543	3960.322	3058.818	2924976	1.79E+08		88706014	NaN	19813280930
9592.789	3083.137	3392.763	2534620	1.55E+08		80541286	NaN	9123370281
9160.915	2518.868	3189.764	2234435	1.35E+08		75176611	NaN	-2275437907
9642.938	2792.133	2956.867	2142955	1.31E+08		74410852	NaN	-6615458456
4.902305	4.493854	58.71616	10166850	3.18E+08		1.54E+08	NaN	33166074220
40.07435	38.81835	196.3347	10420980	3.48E+08		1.64E+08	NaN	35488818040
253.9978	248.2736	462.0992	7894477	3.58E+08		1.62E+08	NaN	39860114910
543.5984	517.9706	741.6077	5238015	3.31E+08		1.44E+08	NaN	40958095380

1461.163	1336.332	1315.353	4443136	3.12E+08	1.36E+08	NaN	41498599290
3629.455	3237.387	2194.654	3655778	2.98E+08	1.25E+08	NaN	40020968430
5968.284	4887.702	2579.446	3274412	2.66E+08	1.19E+08	NaN	37734730150
8790.074	5745.356	2768.666	2991351	2.29E+08	1.13E+08	NaN	32323002280
10580.37	5265.504	3220.98	2611052	1.91E+08	1.03E+08	NaN	24455647950
10931.2	4539.917	3538.122	2274801	1.62E+08	89280899	NaN	17307671060
10630.27	3941.984	3403.578	1954180	1.4E+08	77464208	NaN	11079046390
4.902305	4.493854	58.71616	10166850	3.18E+08	1.54E+08	NaN	33166074220
40.07435	38.81835	196.3347	10420980	3.48E+08	1.64E+08	NaN	35488818040
253.8592	248.1587	461.8882	7955021	3.66E+08	1.64E+08	NaN	40069003910
537.767	513.4432	733.804	5752160	3.81E+08	1.63E+08	NaN	42653234050
1412.255	1300.742	1295.155	4851265	3.9E+08	1.58E+08	NaN	43778496100
3444.046	3115.606	2149.746	3782655	3.8E+08	1.48E+08	NaN	42454757820
5616.793	4843.553	2502.719	3271831	3.62E+08	1.41E+08	NaN	41601928390
8186.35	6173.347	2665.757	3005288	3.39E+08	1.38E+08	NaN	39217531580
10594.35	6612.197	2988.763	2631899	3.05E+08	1.36E+08	NaN	33392293950
11387.18	6077.83	3082.226	2260235	2.73E+08	1.32E+08	NaN	28618413900
10981.92	5335.141	3019.136	1972020	2.46E+08	1.29E+08	NaN	24612913580
3.7	3.4	55.351	6897883	3.34E+08	1.47E+08	NaN	37767241830
39.781	38.05	254.922	7033091	3.26E+08	1.5E+08	NaN	40313502030
259.191	257.46	653.669	5953591	3.3E+08	1.52E+08	NaN	40931321740
1239.157	1226.951	2182.785	5042782	2.68E+08	1.51E+08	NaN	23633128530
2544.946	2488.794	4718.195	4466717	2.2E+08	1.32E+08	NaN	11524129400
4807.605	4653.824	6720.197	3953877	1.92E+08	1.16E+08	NaN	3778922018
7292.842	6951.625	8592.491	3492772	1.69E+08	1.02E+08	NaN	-1510684608
10635.17	9976.307	11241.47	2978596	1.47E+08	92033232	NaN	-6540368386
12784.66	11665.13	14350.26	2456218	1.27E+08	83271741	NaN	-10608864180
15765.84	14005.63	17454.23	2022746	1.13E+08	75616620	NaN	-12410880580
20556.68	17850.64	21263.45	1882179	1.03E+08	68898560	NaN	-13048889880
3.7	3.4	55.668	6897921	3.34E+08	1.47E+08	NaN	37770820260
39.781	38.05	255.239	7032949	3.27E+08	1.5E+08	NaN	40294322570
259.181	257.45	652.475	5962082	3.31E+08	1.51E+08	NaN	40656969190
360.494	358.913	1556.941	5395076	3.08E+08	1.6E+08	NaN	34541602380
823.885	823.885	2516.159	4814379	2.7E+08	1.53E+08	NaN	26305611870
1959.471	1948.031	3682.721	4197154	2.44E+08	1.42E+08	NaN	16330601410
3538.011	3488.125	5074.169	3649116	2.26E+08	1.29E+08	NaN	9247853483
6197.911	6057.543	6890.792	3129527	2.18E+08	1.18E+08	NaN	2010280498
9116.889	8807.56	10286.83	2652950	2E+08	1.08E+08	NaN	-4045766822
13017.6	12412.79	15150.51	2214105	1.76E+08	98074308	NaN	-6495753010
19097.87	18021.52	21010.35	2041940	1.56E+08	89623261	NaN	-8357277098
3.7	3.4	55.668	6897921	3.34E+08	1.47E+08	NaN	37770833690
39.781	38.05	255.239	7032939	3.27E+08	1.5E+08	NaN	40294283120
259.181	257.45	648.413	5954571	3.33E+08	1.54E+08	NaN	41685860990
290.108	288.527	1210.556	5551665	3.37E+08	1.66E+08	NaN	42031556660
507.87	507.87	2127.393	5092204	3.02E+08	1.62E+08	NaN	38219667350
1138.34	1138.34	3282.19	4528868	2.78E+08	1.56E+08	NaN	32611938560
2433.64	2433.64	4538.994	3926427	2.57E+08	1.47E+08	NaN	24302660540

3951.654	3947.478	5643.336	3280636	2.49E+08	1.38E+08	NaN	15423403940
5660.827	5630.586	7046.438	2686918	2.43E+08	1.27E+08	NaN	7974427459
8966.094	8866.533	10342.8	2356392	2.31E+08	1.17E+08	NaN	1860016865
12294.81	12060.32	15088.78	2305570	2.12E+08	1.06E+08	NaN	-1418092488
3.7	3.4	55.668	6897921	3.34E+08	1.47E+08	NaN	37770827990
39.781	38.05	255.239	7032940	3.27E+08	1.5E+08	NaN	40294293820
259.181	257.45	586.564	5950466	3.36E+08	1.55E+08	NaN	42284928730
267.815	266.234	1197.518	5587177	3.47E+08	1.67E+08	NaN	44385654470
365.293	365.293	1937.532	5162646	3.32E+08	1.71E+08	NaN	44491570780
670.059	670.059	2900.356	4620340	3.12E+08	1.67E+08	NaN	42832156140
1317.231	1317.231	4336.712	4176487	2.91E+08	1.6E+08	NaN	39042389740
2692.117	2692.117	5505.533	3639191	2.81E+08	1.52E+08	NaN	34193217950
4044.339	4044.339	6345.111	3016475	2.69E+08	1.44E+08	NaN	25823818090
6636.43	6630.519	7370.602	2425261	2.62E+08	1.34E+08	NaN	15468528590
8900.084	8879.072	9993.309	2190230	2.57E+08	1.23E+08	NaN	9115046702
3.7	3.4	55.668	6897921	3.34E+08	1.47E+08	NaN	37770773340
39.781	38.05	255.239	7032940	3.27E+08	1.5E+08	NaN	40294276410
259.181	257.45	577.031	5955364	3.39E+08	1.57E+08	NaN	42392228060
260.893	259.312	1070.444	5639539	3.62E+08	1.68E+08	NaN	46125215530
274.78	274.78	1627.025	5243723	3.73E+08	1.76E+08	NaN	49544828530
311.474	311.474	2537.575	4745865	3.68E+08	1.8E+08	NaN	52585738920
666.343	666.343	3798.951	4324438	3.54E+08	1.78E+08	NaN	54663549370
1471.99	1471.99	5229.015	3780013	3.46E+08	1.74E+08	NaN	55537153420
2648.202	2648.202	6584.746	3287629	3.27E+08	1.69E+08	NaN	55974066830
4307.712	4307.712	7574.665	2840070	3.15E+08	1.61E+08	NaN	56218816630
5843.083	5839.483	7967.439	2592205	2.9E+08	1.53E+08	NaN	55426330740
3.7	3.4	55.668	6897915	3.34E+08	1.47E+08	NaN	37768994360
39.781	38.05	255.239	7032933	3.27E+08	1.5E+08	NaN	40294638280
259.181	257.45	540.752	5989514	3.45E+08	1.58E+08	NaN	42262425250
257.331	255.75	932.293	5669987	3.73E+08	1.69E+08	NaN	46727550650
238.229	238.229	1419.024	5271352	3.93E+08	1.77E+08	NaN	51606451500
159.66	159.66	2121.885	4853472	4.11E+08	1.83E+08	NaN	56651629190
382.054	382.054	3134.374	4443642	4.26E+08	1.87E+08	NaN	61402269010
899.171	899.171	4362.284	3947394	4.33E+08	1.88E+08	NaN	65996979000
1335.941	1335.941	5090.801	3434581	4.36E+08	1.87E+08	NaN	74133629280
2096.954	2096.954	6253.277	2952570	4.34E+08	1.87E+08	NaN	81028376880
3374.932	3374.932	7950.278	2717675	4.22E+08	1.86E+08	NaN	85684204390
1.2895	1.2895	35.3325	8334800	3.5E+08	1.7E+08	NaN	34373934500
11.877	11.877	43.2872	7903800	3.76E+08	1.85E+08	NaN	39398615600
26.7852	26.7852	106.4602	8340500	4.24E+08	2.15E+08	NaN	46637736200
134.9159	134.9159	434.5027	8348000	4.58E+08	2.42E+08	NaN	48292181400
590.6526	590.6526	1107.792	6578600	3.43E+08	2.09E+08	NaN	32552846300
1230.742	1230.742	1674.147	6182300	2.94E+08	2E+08	NaN	22930895200
1836.412	1836.412	2486.241	5798800	3.01E+08	2.1E+08	NaN	16754039300
2650.958	2650.958	3793.876	5327600	2.96E+08	2.14E+08	NaN	9494704600
3895.256	3895.256	5281.18	4959700	2.94E+08	2.18E+08	NaN	3925184500
5353.665	5353.665	7135.913	4670700	2.93E+08	2.23E+08	NaN	-713415000

7078.745	7078.745	9049.08	4462100	2.94E+08	2.27E+08	NaN	-3861942700
1.2895	1.2895	35.3325	8334800	3.5E+08	1.7E+08	NaN	34373934500
11.877	11.877	43.2872	7903800	3.76E+08	1.85E+08	NaN	39398615600
26.7852	26.7852	106.4602	8340500	4.24E+08	2.15E+08	NaN	46637736200
102.2534	102.2534	311.8137	8385700	4.68E+08	2.44E+08	NaN	50589140800
335.3812	335.3812	657.2819	7293100	3.73E+08	2.26E+08	NaN	43026225700
746.8559	746.8559	1054.178	6842900	3.47E+08	2.22E+08	NaN	36561864000
1276.55	1276.55	1730	6157400	3.37E+08	2.26E+08	NaN	25470368300
1694.822	1694.822	2341.542	5824900	3.45E+08	2.36E+08	NaN	19713865200
2210.791	2210.791	3163.73	5447000	3.51E+08	2.46E+08	NaN	15958927700
3026.237	3026.237	4336.894	5073700	3.52E+08	2.53E+08	NaN	11400028500
4249.112	4249.112	5902.378	4735100	3.47E+08	2.55E+08	NaN	6401836300
1.2895	1.2895	35.3325	8334800	3.5E+08	1.7E+08	NaN	34373934500
11.877	11.877	43.2872	7903800	3.76E+08	1.85E+08	NaN	39398615600
26.7852	26.7852	106.4602	8340500	4.24E+08	2.15E+08	NaN	46637736200
100.3114	100.3114	304.5432	8388600	4.7E+08	2.45E+08	NaN	50805267700
282.7516	282.7516	563.8515	7713300	4.08E+08	2.39E+08	NaN	48074469800
573.4055	573.4055	821.7309	7336600	3.93E+08	2.4E+08	NaN	46888112200
822.4284	822.4284	1127.665	7000600	4.2E+08	2.6E+08	NaN	48048435800
1105.647	1105.647	1516.401	6500800	4.24E+08	2.7E+08	NaN	43526677200
1496.907	1496.907	2060.77	6002100	4.29E+08	2.81E+08	NaN	37554195400
1897.121	1897.121	2656.928	5606800	4.43E+08	2.93E+08	NaN	33712190900
2349.263	2349.263	3387.528	5250600	4.53E+08	3.04E+08	NaN	31248202100
1.2895	1.2895	35.3325	8334800	3.5E+08	1.7E+08	NaN	34373934500
11.7908	11.7908	43.4013	7907600	3.77E+08	1.85E+08	NaN	39560752300
19.4	19.4	57.1599	8366100	4.36E+08	2.19E+08	NaN	48502706900
33.1709	33.1709	75.2413	8392600	4.9E+08	2.49E+08	NaN	55000886500
53.8618	53.8618	95.8726	8478400	5.34E+08	2.75E+08	NaN	59877305400
81.5896	81.5896	114.2928	8160500	5.75E+08	2.99E+08	NaN	64001363000
108.3326	108.3326	153.5991	7636100	6.15E+08	3.22E+08	NaN	67962295200
139.5087	139.5087	200.2114	7169500	6.55E+08	3.46E+08	NaN	71792665700
186.9195	186.9195	269.4603	6686300	6.95E+08	3.69E+08	NaN	75571458400
241.6192	241.6192	349.4753	6254300	7.34E+08	3.91E+08	NaN	80137183400
309.9962	309.9962	450.7418	5842600	7.74E+08	4.13E+08	NaN	85214965500
				1.8E+08			
18.787		92.87807	7718362	3.68E+08	1.93E+08	1.75E+08 NaN	35775762530
209.0308		404.5147	7466236	3.94E+08	1.98E+08	1.96E+08 NaN	40048785360
587.7284		1277.995	6513433	3.45E+08	1.39E+08	2.05E+08 NaN	23821810490
1192.871		1968.717	6340488	3.58E+08	1.36E+08	2.22E+08 NaN	16324223230
2087.153		2398.587	6135944	3.57E+08	1.2E+08	2.38E+08 NaN	11881383240
3205.443		2401.154	5551899	3.57E+08	1.09E+08	2.48E+08 NaN	6666028153
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18.78684		92.8781	7718361	3.68E+08	1.93E+08	1.75E+08 NaN	35775762490

209.0309	404.5145	7466235	3.94E+08	1.98E+08	1.96E+08	NaN	40048796730	
501.24	901.5399	6802658	3.69E+08	1.58E+08	2.11E+08	NaN	35021114670	
1043.843	1561.587	6539055	3.84E+08	1.55E+08	2.29E+08	NaN	28099447300	
1872.604	2061.328	6111320	3.81E+08	1.36E+08	2.45E+08	NaN	19939745670	
2947.763	2305.174	5562365	3.8E+08	1.23E+08	2.57E+08	NaN	14798745000	
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4940.425	2528.199	4650051	3.66E+08	93701918	2.72E+08	NaN	2773520564	
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18.78684	92.8781	7718361	3.68E+08	1.93E+08	1.75E+08	NaN	35775762450	
209.0309	404.5145	7466235	3.94E+08	1.98E+08	1.96E+08	NaN	40048795810	
463.2488	781.4397	7031678	3.84E+08	1.7E+08	2.14E+08	NaN	39451086240	
944.7735	1274.394	6755184	4.04E+08	1.7E+08	2.34E+08	NaN	36566084270	
1705.505	1721.088	6270053	4.03E+08	1.51E+08	2.52E+08	NaN	29034578190	
2748.928	2125.479	5644192	3.98E+08	1.35E+08	2.63E+08	NaN	21480445160	
3853.717	2358.573	5161175	3.92E+08	1.18E+08	2.74E+08	NaN	15715357360	
4476.949	2173.831	4063033	4.01E+08	1.13E+08	2.88E+08	NaN	10931517500	
4967.126	2090.233	3619322	4.06E+08	1.06E+08	2.99E+08	NaN	9782592244	
5657.641	2317.973	3361681	4.05E+08	95610164	3.08E+08	NaN	7694019169	
			1.8E+08					
18.78684	92.8781	7718361	3.68E+08	1.93E+08	1.75E+08	NaN	35775762450	
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2125.656	1243.843	6310183	4.79E+08	1.91E+08	2.88E+08	NaN	47612523330	
2923.487	1357.16	5629815	4.75E+08	1.74E+08	3.01E+08	NaN	44591015670	
3674.966	1650.892	4864903	4.63E+08	1.52E+08	3.11E+08	NaN	36805763550	
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760.1534	929.2422	7562722	5.25E+08	2.75E+08	2.5E+08	NaN	53846928810	
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2705.515	1179.41	5903478	5.75E+08	2.62E+08	3.13E+08	NaN	55898208470	
3307.738	1357.156	5161018	5.7E+08	2.4E+08	3.3E+08	NaN	51172922990	
3810.335	1502.615	4485016	5.68E+08	2.24E+08	3.44E+08	NaN	47532718760	
4281.432	1648.492	3826581	5.62E+08	2.05E+08	3.57E+08	NaN	44784721730	
1.053	1.053	39.69	6741900	3.34E+08	1.06E+08	1.57E+08	NaN	35280000000
39.35	38.82	180.4	6625300	3.71E+08	1.22E+08	1.71E+08	NaN	36370000000
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1.053	1.053	39.69	6725500	3.34E+08	1.06E+08	1.57E+08	NaN	35229942500
39.35	38.82	180.4	6710000	3.71E+08	1.22E+08	1.72E+08	NaN	36335005000
269.5	265.1	514.7	6409600	3.91E+08	1.24E+08	2.04E+08	NaN	39561252300
285.8	273.6	911.8	5502500	3.39E+08	86520000	2.07E+08	NaN	43164648300
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1.053	1.053	39.69	6725500	3.34E+08	1.06E+08	1.57E+08	NaN	35229942500
39.35	38.82	180.4	6710000	3.71E+08	1.22E+08	1.72E+08	NaN	36335005000
269.5	265.1	514.7	6410600	3.91E+08	1.24E+08	2.04E+08	NaN	39549850200
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1.053	1.053	39.69	6725500	3.34E+08	1.06E+08	1.57E+08	NaN	35229942500
39.35	38.82	180.4	6710000	3.71E+08	1.22E+08	1.72E+08	NaN	36335005000
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22440	14850	14600	2609800	2.1E+08	25990000	1.61E+08	NaN	17166311100
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1.053	1.053	39.69	6725500	3.34E+08	1.06E+08	1.57E+08	NaN	35229942500
39.35	38.82	180.4	6709000	3.71E+08	1.22E+08	1.72E+08	NaN	36335005000
269.5	265.1	514.7	6409600	3.91E+08	1.24E+08	2.04E+08	NaN	39560359500
254.6	250.3	705.8	5755800	4.15E+08	1.26E+08	2.28E+08	NaN	47835990100
188.9	184.9	907.5	5110500	4.23E+08	1.23E+08	2.45E+08	NaN	54512741600
142.5	129.3	1526	4171300	4.03E+08	1.15E+08	2.4E+08	NaN	58172971300
907.2	804.2	2643	3756600	3.66E+08	95480000	2.3E+08	NaN	58939778700
3600	3123	4705	3375400	3.26E+08	74720000	2.18E+08	NaN	55299005200

8851	7334	7843	3083300	2.77E+08	55720000	1.94E+08	NaN	50540137300
15930	12260	11840	2801300	2.36E+08	42720000	1.69E+08	NaN	44186311100
23160	16410	14150	2543100	2.02E+08	34390000	1.44E+08	NaN	40968865200
1.053	1.053	39.69	6741900	3.34E+08	1.06E+08	1.57E+08	NaN	35279640500
39.35	38.82	180.4	6624300	3.71E+08	1.22E+08	1.71E+08	NaN	36371124600
269.5	265.1	484.5	6682800	4.08E+08	1.21E+08	2.19E+08	NaN	44610389300
254.6	250.3	560.1	6081300	4.77E+08	1.4E+08	2.64E+08	NaN	56726452000
183.3	180.1	538.5	5474300	5.7E+08	1.86E+08	3.08E+08	NaN	69861617000
22.5	20.72	936.7	4490500	6.31E+08	2.1E+08	3.32E+08	NaN	84436466100
43.59	36.26	1736	4027200	6.45E+08	2.28E+08	3.36E+08	NaN	1.01302E+11
352.5	305.6	2845	3649000	6.46E+08	2.37E+08	3.31E+08	NaN	1.175E+11
1673	1449	4396	3356300	6.21E+08	2.3E+08	3.15E+08	NaN	1.29499E+11
5083	4295	6864	3016200	5.83E+08	2.24E+08	2.84E+08	NaN	1.30398E+11
10410	8353	9328	2683600	5.4E+08	2.05E+08	2.45E+08	NaN	1.26098E+11

CO2 emissions (BECCS)	CO2 emissions (CCS)	Fossil CO2 emissions	Land CO2 emissions	F-gas emissions	Kyoto gas emisison	Nitrous oxide emissions	Land nitrous oxide emissions
0	0	29394248380	3771829776	6.73E+08	4.45E+10	9156453	6874411
0	0	31981488160	3507338835	8.78E+08	4.8E+10	9831880	7486986
48300128.47	181468957.1	30554137570	2654661229	1.59E+09	4.51E+10	9276022	7310205
1001573983	2510513471	17442727580	525239686	9.6E+08	2.66E+10	7595500	7017176
3547881355	8466587109	5342759350	1071187443	2.01E+08	1.34E+10	7678852	7237962
4244053177	10766619420	1609828849	-641792978	2.01E+08	7.26E+09	7570986	7181883
5180821375	12368708430	-316956993	-1.333E+09	1.86E+08	4.41E+09	7602241	7225174
6748824947	14600111380	-2441226653	-1.696E+09	1.98E+08	1.77E+09	7763508	7375831
9072973656	15589320970	-5286835066	-2.083E+09	2.04E+08	-1.6E+09	7995745	7581611
11448356010	16076111720	-8181154877	-2.387E+09	2.05E+08	-5E+09	8115737	7678941
14863338630	17904460390	-1.1956E+10	-2.384E+09	1.97E+08	-8.9E+09	8304321	7806639
0	0	29394248380	3771829776	6.73E+08	4.45E+10	9156453	6874411
0	0	31981486300	3507338835	8.78E+08	4.8E+10	9831880	7486986
0	0.000988881	35747980190	2641799594	1.59E+09	5.07E+10	9423506	7297469
18086619.37	524065015	33774290820	156634828	1.23E+09	4.41E+10	8282467	7069792
579823728.1	3298166839	26247477800	-342740571	3.01E+08	3.4E+10	7744856	6973778
1571773140	5549699388	19333121840	-1.6E+09	2.01E+08	2.5E+10	7593677	6965591
3406105493	8620201536	13000064510	-2.434E+09	1.87E+08	1.74E+10	7593437	6997674
5531164173	11074010720	7288206169	-2.503E+09	2E+08	1.12E+10	7705696	7176346
9437241775	14819451400	-474654898	-2.447E+09	2.05E+08	3.06E+09	8025622	7523306
12869307720	17942193080	-6002102559	-2.096E+09	2.05E+08	-2.1E+09	8541920	7969961
11905838950	16210222530	-5455439498	-2.892E+09	1.97E+08	-2.7E+09	8354563	7830376
0	0	29394248380	3771829776	6.73E+08	4.45E+10	9156453	6874411
0	0	31981483730	3507338835	8.78E+08	4.8E+10	9831880	7486986
2.70E-17	2.75811E-06	36882478030	2756302610	1.73E+09	5.32E+10	10031736	7592137
2.68E-17	846167.703	38624051270	727344026	2.15E+09	5.21E+10	9583044	7219632
40209.217	18249570.17	37437271410	5857696.14	1.85E+09	4.86E+10	8818760	7102811
1624083.599	180133601.2	34600764420	-1.653E+09	1.58E+09	4.3E+10	8299699	7037538
83991789.47	937278232	30959729340	-3.004E+09	8.2E+08	3.65E+10	7958206	6984294
699327848	2977974101	23490119140	-3.677E+09	3.18E+08	2.69E+10	7679417	7033498
3001087249	6698987919	13161433990	-4.038E+09	2.05E+08	1.55E+10	7689181	7174649
8500910441	12814245630	1222890729	-3.498E+09	2.05E+08	3.75E+09	8224124	7707124
11460774660	15622254410	-3862332290	-2.753E+09	1.98E+08	-5.6E+08	8709586	8122395
0	0	29394248380	3771829776	6.73E+08	4.45E+10	9156453	6874411
0	0	31981483730	3507338835	8.78E+08	4.8E+10	9831880	7486986
3.70E-13	2.53074E-06	36878281680	2981847515	1.73E+09	5.35E+10	10072584	7630968
5632.408	465017.708	39609203090	1348884106	2.34E+09	5.46E+10	9992092	7434233

5609.29	3245045.894	40999569500	499018915	3.12E+09	5.54E+10	9848718	7330992
3645.922	8648049.931	41131823270	-1.111E+09	3.59E+09	5.4E+10	9771553	7261805
0.00026718	26231309.78	39869303650	-2.135E+09	3.21E+09	5.03E+10	9216565	7007165
0	64835342.57	34822086520	-2.499E+09	2.7E+09	4.33E+10	8517984	7017335
107766803.5	549812019.3	27142304760	-2.687E+09	1.55E+09	3.32E+10	7976796	7178367
746724340	1754321235	19869667600	-2.562E+09	9.51E+08	2.46E+10	7795871	7277055
1966141097	3320564857	14046561140	-2.968E+09	9.12E+08	1.78E+10	7658984	7236095
0	0	29394248380	3771829776	6.73E+08	4.45E+10	9156453	6874411
0	0	31981483730	3507338835	8.78E+08	4.8E+10	9831880	7486986
0	0	36892236180	3176769580	1.73E+09	5.4E+10	10193926	7747131
0	0	39680275450	2972975654	2.35E+09	5.77E+10	10514839	7926474
0	0	41860775850	1917707024	3.14E+09	5.98E+10	10616954	7938957
0	0	42668609650	-213854482	3.6E+09	5.87E+10	10498269	7832364
0	0	43038298390	-1.436E+09	3.96E+09	5.77E+10	10268842	7676166
0	0	40936403490	-1.719E+09	4.36E+09	5.51E+10	10159419	7752950
0	0	35332480670	-1.94E+09	4.74E+09	4.87E+10	10014053	7924046
0	0	30633360380	-2.015E+09	4.86E+09	4.32E+10	9825722	8048353
0	0	27049003560	-2.436E+09	4.67E+09	3.82E+10	9418887	7948266
0	0	30872683090	6894558733	5.48E+08	4.9E+10	8286062	6106337
0	0	33151923900	7161578136	7.33E+08	5.18E+10	8748512	6443245
0	0	36454559350	4476762383	1.5E+09	5.35E+10	9564997	6983375
67415333.33	1845829333	22911514290	721614238	8.68E+08	3.41E+10	9770745	7378650
363495000	5694960333	13019793930	-1.496E+09	8.56E+08	2.06E+10	9218903	7068786
1313429333	8602110000	6064363433	-2.285E+09	9.21E+08	1.19E+10	8196763	6467859
3293004000	9090268000	1875603819	-3.386E+09	9.53E+08	5.86E+09	7417859	5790486
7205286000	10568580000	-2972924572	-3.567E+09	9.47E+08	9374058	6556566	5295827
10720284670	12510168000	-6872422068	-3.736E+09	9.31E+08	-4.7E+09	6111998	4822445
11628235670	12918693330	-8159471231	-4.251E+09	9.09E+08	-7E+09	5636218	4384968
12361767000	13606992670	-8886574330	-4.162E+09	9.07E+08	-8E+09	5251328	4007440
0	0	30875871770	6894948483	5.48E+08	4.9E+10	8285953	6106337
0	0	33132878790	7161443786	7.33E+08	5.18E+10	8758093	6443245
0	14798666.67	36219184280	4437784919	1.49E+09	5.33E+10	9580786	6976084
61189333.33	1149261667	31750765980	2790836408	9.87E+08	4.63E+10	10277922	7599065
256457666.7	4564640667	26208463810	97148063.9	1.06E+09	3.72E+10	10349797	7781372
828157000	11005459670	18325215930	-1.995E+09	1.15E+09	2.65E+10	9923819	7693109
2459310333	16585477330	12620939560	-3.373E+09	1.1E+09	1.88E+10	9441261	7314837
5930734333	22888701000	5288097573	-3.278E+09	1.12E+09	1.12E+10	8757517	6910593
8666984333	24607289670	214677135.3	-4.26E+09	1.13E+09	4.39E+09	7835717	6465640
10180327670	23031107000	-2646276598	-3.849E+09	1.13E+09	1.17E+09	7268904	5940648
11366424670	20883863000	-4570578650	-3.787E+09	1.15E+09	-1.3E+09	6671173	5423402
0	0	30875885210	6894948483	5.48E+08	4.9E+10	8285953	6106337
0	0	33132839330	7161443786	7.33E+08	5.18E+10	8758093	6443245
0	6600000	36374401860	5311459130	1.49E+09	5.44E+10	9631906	7026713
20804666.67	238788000	37890790320	4140766338	1.33E+09	5.49E+10	10533281	7726294
118488333.3	1272102333	36303415400	1916251951	1.26E+09	5.03E+10	10912855	8069431
458403000	3753273333	33526900250	-914961693	1.23E+09	4.4E+10	10885182	8196909
1541345667	9559905667	26728912900	-2.426E+09	1.28E+09	3.51E+10	10501365	8068474

4020786000	18223894330	18553511950	-3.13E+09	1.32E+09	2.59E+10	10011508	7846793
6248308000	25325292670	11941196540	-3.967E+09	1.23E+09	1.79E+10	9009501	7539847
7699860667	28697324330	6617872360	-4.758E+09	1.25E+09	1.14E+10	8466669	7058645
9249130000	30033615330	3010926951	-4.429E+09	1.27E+09	7.51E+09	7935093	6488844
0	0	30875879500	6894948483	5.48E+08	4.9E+10	8285953	6106337
0	0	33132850030	7161443786	7.33E+08	5.18E+10	8758092	6443245
0	0	36614540740	5670387997	1.49E+09	5.5E+10	9657447	7049354
6537666.667	78829666.67	39797164350	4588490119	1.54E+09	5.77E+10	10608980	7766986
36586000	415873333.3	41313937900	3177632881	1.43E+09	5.75E+10	11182377	8241589
151033666.7	1329727667	42149946470	682209671	1.27E+09	5.53E+10	11372071	8506016
468629333.3	3384582667	40998072440	-1.956E+09	1.34E+09	5.1E+10	11265046	8555433
1350433333	7474463333	36823849840	-2.631E+09	1.39E+09	4.58E+10	10868119	8450018
3052155333	14496617670	29625244140	-3.801E+09	1.41E+09	3.69E+10	9965779	8241015
4914063000	23273308670	20027979270	-4.559E+09	1.44E+09	2.62E+10	9361891	7885944
6361483333	31789710330	13915123670	-4.8E+09	1.37E+09	1.95E+10	8776604	7415498
0	0	30875824860	6894948483	5.48E+08	4.9E+10	8285953	6106337
0	0	33132832630	7161443786	7.33E+08	5.18E+10	8758093	6443245
0	0	36732975960	5659252105	1.49E+09	5.52E+10	9686537	7077714
0	0	41457853860	4667361668	1.81E+09	6.02E+10	10669539	7791600
0	0	45673434400	3871394132	2.29E+09	6.45E+10	11386542	8365284
0	0	50303836400	2281902526	2.58E+09	6.79E+10	11755891	8783467
0	86969666.67	54122052590	541496776	2.68E+09	6.97E+10	11898688	9022266
0	560681000	56403334390	-866180966	2.23E+09	6.99E+10	11805878	9134691
2156000	1910692667	58649808720	-2.676E+09	1.5E+09	6.9E+10	11383193	9105311
24522666.67	4893977000	60196809370	-3.978E+09	1.56E+09	6.9E+10	11345697	8962341
100455666.7	7979198333	59696348950	-4.27E+09	1.63E+09	6.76E+10	11193341	8696078
0	0	30874045870	6894948483	5.48E+08	4.9E+10	8285950	6106337
0	0	33133194490	7161443786	7.33E+08	5.18E+10	8758082	6443245
0	0	37148024860	5114400392	1.51E+09	5.53E+10	9742624	7099679
0	0	42507302020	4220248626	1.97E+09	6.13E+10	10959872	7806830
0	0	47740715230	3865736274	2.43E+09	6.74E+10	11930028	8402180
0	0	53614470790	3037158405	2.89E+09	7.36E+10	12689418	8869951
0	0	59467087800	1935181211	3.38E+09	7.93E+10	13157974	9210878
0	0	65089404510	907574490	4.02E+09	8.48E+10	13459986	9423901
0	0	74067977700	65651579.8	4.69E+09	9.39E+10	13872232	9550357
0	0	81276948460	-248571578	5.37E+09	1.02E+11	14478796	9609625
0	0	86165767690	-481563299	6.06E+09	1.07E+11	15094255	9618958
0	0	29596083800	4777850700	5.32E+08	4.63E+10	8950428	6313233
0	0	32480035400	6918580200	7.48E+08	5.24E+10	9664651	6885117
0	0	39493257100	7144479100	8.55E+08	6.14E+10	10993034	7984993
0	0	42677379000	5614802400	4.55E+08	6.38E+10	11970619	8989430
316645900	3089636300	29327171000	3225675200	3.33E+08	4.44E+10	9835121	7707130
2422931400	10527017400	21171744300	1759150800	99106100	3.35E+10	10374127	8562131
5095818300	16985182600	14495744600	2258294700	88768800	2.76E+10	10827643	9054788
7895301900	18000532100	8290314000	1204390700	84219300	2.02E+10	10938404	9356065
9787142700	18404618500	3568871200	356313300	81037400	1.47E+10	11080860	9644234
11407319100	18565512200	-396494300	-316920700	78039900	1.01E+10	11240519	9908333

12639289900	18560994000	-3347244900	-514697800	76554200	6.98E+09	11425757	10157225
0	0	29596083800	4777850700	5.32E+08	4.63E+10	8950428	6313233
0	0	32480035400	6918580200	7.48E+08	5.24E+10	9664651	6885117
0	0	39493257100	7144479100	1.08E+09	6.16E+10	10993034	7984993
0	0	44837617900	5751522800	1.03E+09	6.7E+10	12268201	9087305
0	554381800	39322943600	3703282200	6.48E+08	5.62E+10	10814857	8372249
254794900	4720187600	33453629700	3108234400	3.19E+08	4.9E+10	11430567	9183179
2866992500	12478443700	22896697100	2573671100	4.17E+08	3.78E+10	11578524	9526728
5957084500	17682157700	17228383900	2485481400	3.76E+08	3.23E+10	12033261	10037675
7305074700	19369549700	14328994100	1629933700	3.73E+08	2.88E+10	12426462	10500535
8821674400	20567955200	10742908600	657119900	1.1E+08	2.41E+10	12670620	10843636
10637467800	21130234200	6260073100	141763200	3.09E+08	1.92E+10	12737918	11042824
0	0	29596083800	4777850700	5.32E+08	4.63E+10	8950428	6313233
0	0	32480035400	6918580200	7.48E+08	5.24E+10	9664651	6885117
0	0	39493257100	7144479100	1.15E+09	6.17E+10	10993034	7984993
0	0	45038009600	5767258100	1.24E+09	6.75E+10	12305752	9099834
0	2850000	43900313000	4174156800	1.18E+09	6.29E+10	11580485	8848924
0	404552900	43170493200	3717618900	1.08E+09	6.15E+10	12303306	9671239
0	756389300	43682796800	4365639000	1.19E+09	6.37E+10	13165761	10468250
0	2982843900	39840726500	3685950700	9.28E+08	5.91E+10	13586151	11007236
377485000	7454211100	35043513100	2510682300	8.14E+08	5.33E+10	14017275	11519289
1686761200	12738987400	31325724700	2386466200	7.07E+08	4.98E+10	14603967	12089257
3454191200	16334610000	28617158800	2631043300	8.04E+08	4.79E+10	15122359	12599470
		29596083800	4777850700	5.32E+08	4.63E+10	8950428	6313233
		32637746100	6923006200	7.48E+08	5.26E+10	9696905	6890739
		41088257200	7414449600	1.16E+09	6.39E+10	11340142	8111850
		49158915300	5841971200	1.3E+09	7.24E+10	12869535	9271320
		55239447900	4637857400	1.44E+09	7.89E+10	14145163	10273478
		60206473500	3794889500	1.53E+09	8.45E+10	15316645	11235351
		64222705700	3739589600	1.58E+09	8.98E+10	16404087	12158780
		68480647900	3312017800	1.64E+09	9.5E+10	17491047	13071485
		72728153200	2843305300	1.71E+09	1E+11	18562328	13976418
		77572247000	2564936400	1.8E+09	1.06E+11	19618343	14852001
		82558844400	2656121100	1.91E+09	1.13E+11	20656195	15696995
0	1813315031	32646976520	3128786018	9.41E+08	4.6E+10	10629113	8004550
63447843.84	2566112191	38638997820	1409787543	1.13E+09	5.3E+10	11076643	8546870
1558426104	9776825449	24755425680	-933615185	2.48E+08	3.69E+10	10898958	9323329
3650670817	15773641440	16421459180	-97235951	2.45E+08	2.91E+10	11688874	10187774
6237648239	20061980980	9512715803	2368667435	2.6E+08	2.24E+10	12420963	10952498
9532677330	23252746750	1645026937	5021001216	2.74E+08	1.48E+10	13252447	11806898
12663301320	24568908850	-6162634035	6039512586	2.86E+08	7.04E+09	13988388	12559384
15684998540	24992356640	-1.354E+10	2917535882	2.97E+08	-4.1E+08	14395245	12962068
18705289100	26883717840	-2.0063E+10	971396780	3.11E+08	-7.2E+09	14382531	12918876
23713467510	31790895160	-2.7729E+10	184772631	3.33E+08	-1.5E+10	14545515	13017220
0	1813315031	32646976470	3128786018	9.41E+08	4.6E+10	10629113	8004552

63447844.36	2566112191	38638996080	1409800650	1.13E+09	5.3E+10	11076644	8546871
513836331.3	5407643142	36025535260	-1.004E+09	4.87E+08	4.91E+10	11202337	9371571
1343569877	9527415052	29180102130	-1.081E+09	3.51E+08	4.27E+10	11865218	10168825
2690606140	13947034730	20523568250	-583822575	2.63E+08	3.4E+10	12493815	10904899
5005424528	17825592420	12739333940	2059411062	2.7E+08	2.65E+10	13178919	11643347
8040044438	20762954210	5007923513	5239011074	2.78E+08	1.88E+10	13906228	12412662
11206577020	23018415630	-3082679635	5856200199	2.87E+08	1.07E+10	14614628	13153508
14205855820	24003471600	-1.0817E+10	3685234328	2.95E+08	2.88E+09	15071887	13620484
17146466380	25722261680	-1.7439E+10	1477333711	3.05E+08	-4E+09	15110869	13635039

0	1813315031	32646976430	3128786018	9.41E+08	4.6E+10	10629113	8004552
63447844.36	2566112191	38638995160	1409800650	1.13E+09	5.3E+10	11076644	8546871
319340722.8	4402635891	39924554130	-473467893	8.31E+08	5.38E+10	11499234	9458487
728805740.2	6754661587	37337668670	-771584391	5.85E+08	5.17E+10	12143385	10250332
1387229395	9971512924	30044859920	-1.01E+09	3.91E+08	4.43E+10	12723870	10988598
2660596055	13571520230	21167666660	312778505	2.72E+08	3.54E+10	13271694	11641311
4684329802	16665978370	13312564610	2402792751	2.76E+08	2.75E+10	13894998	12330426
5416087424	17101215690	11488394390	-556876893	2.79E+08	2.62E+10	14634682	13072416
5883447851	17499026790	9928128253	-145536010	2.79E+08	2.49E+10	15205340	13657785
7025113686	18194774700	6446823513	1247195656	2.78E+08	2.16E+10	15759038	14237441

0	1813315031	32646976430	3128786018	9.41E+08	4.6E+10	10629113	8004552
63447844.36	2566112191	38638995000	1409800650	1.13E+09	5.3E+10	11076644	8546871
177727733.4	3772848009	45160886470	959892051	2.65E+09	6.29E+10	13014814	9627683
299785137.6	4858995410	47483618380	1511267258	2.9E+09	6.64E+10	13953231	10531886
401609317.9	5746969603	47525229300	1529462049	2.76E+09	6.67E+10	14547569	11419394
548962041.3	6634781779	46201039890	1411483434	2.24E+09	6.5E+10	14982018	12156491
663957157.8	7221827363	43627608290	963407382	1.58E+09	6.17E+10	15251950	12839312
827545261.7	7914499770	37408773430	-603009879	9.51E+08	5.46E+10	15396403	13422229
1110128254	8904439154	30242028090	-1.677E+09	5.21E+08	4.68E+10	15676960	13883899
1686669882	10428045430	22476442520	-1.907E+09	3.5E+08	3.87E+10	16009754	14343027

0	0	29385721490	2501447876	7.57E+08	4.42E+10	9925504	7349251
0	0	32646988710	3128786018	9.41E+08	4.91E+10	10629113	8004552
0	0	40417488040	1218539006	1.75E+09	5.73E+10	11701522	8611060
0	0	47694335230	1375235017	2.77E+09	6.77E+10	13174145	9657130
0	0	51591229000	2255699817	3.1E+09	7.44E+10	14429187	10596362
0	0	53078258600	2586178806	3.33E+09	7.73E+10	15602554	11531024
0	0	53691959560	3262017104	3.46E+09	7.94E+10	16613990	12330270
0	0	52929922310	2968286161	3.54E+09	7.91E+10	17606023	13121766
0	0	49420809640	1752113352	3.56E+09	7.45E+10	18493649	13882043
0	0	46575217220	957501541	3.54E+09	7.1E+10	19312971	14520689
0	0	44329322090	455399639	3.51E+09	6.97E+10	20173531	15168227
0	0	29550000000	5733000000	6.73E+08	4.76E+10	9813947	7167947
0	0	32200000000	4170000000	8.7E+08	5E+10	10277903	7844903

168000	702000	38370000000	1321000000	1.41E+09	5.45E+10	10769411	8602411
590000000	694000000	36130000000	1643000000	9.09E+08	4.92E+10	9806412	8081412
6600000000	7170000000	17730000000	4408000000	1.87E+08	3.19E+10	10855107	9145107

16100000000	16800000000	-3893000000	5147000000	1.49E+08	1.08E+10	12740634	10870634
19200000000	19900000000	-1.416E+10	1317000000	1.53E+08	-3.8E+09	12543652	10623652
20500000000	21000000000	-1.711E+10	859900000	1.77E+08	-7.6E+09	12002279	9982279
21600000000	21700000000	-1.863E+10	704400000	1.78E+08	-9.5E+09	12187886	9997886
22100000000	22200000000	-1.945E+10	-102300000	1.72E+08	-1.2E+10	11728601	9438601
22500000000	22500000000	-2.011E+10	-1.201E+09	1.83E+08	-1.4E+10	11234967	8914967
0	0	29550000000	5682942500	6.73E+08	4.76E+10	9806726	7160726
0	0	32200000000	4135005000	8.7E+08	5E+10	10300588	7867588
168000	702000	38370000000	1182252300	1.41E+09	5.45E+10	10758180	8591180
134000000	369000000	41610000000	1548648300	9.09E+08	5.6E+10	10458312	8638312
1700000000	4010000000	35770000000	2248976700	1.87E+08	4.86E+10	9976049	8334049
7430000000	12000000000	21150000000	3832273800	1.49E+08	3.51E+10	10483699	8973699
14000000000	18900000000	3784000000	3699276800	1.53E+08	1.72E+10	11884582	10424582
17200000000	21300000000	-6230000000	2240670400	1.77E+08	5.36E+09	12075051	10555051
19400000000	21600000000	-1.242E+10	1072327500	1.78E+08	-2.8E+09	11786224	10096224
21000000000	21900000000	-1.7E+10	507444100	1.72E+08	-8.6E+09	11720263	9720263
22100000000	22600000000	-1.918E+10	202014800	1.83E+08	-1.1E+10	11547910	9297910
0	0	29550000000	5682942500	6.73E+08	4.76E+10	9806726	7160726
0	0	32200000000	4135005000	8.7E+08	5E+10	10300588	7867588
168000	702000	38370000000	1170850200	1.45E+09	5.46E+10	10758180	8591180
43300000	279000000	43100000000	1375965000	1.12E+09	5.87E+10	10718811	8808811
477000000	3050000000	42640000000	887087500	5.64E+08	5.58E+10	10421960	8614960
2020000000	10700000000	36800000000	620238200	1.49E+08	4.8E+10	9272135	7616135
5780000000	17300000000	26140000000	2314157200	1.53E+08	3.85E+10	9587742	8162742
10200000000	20800000000	13000000000	2511429100	1.77E+08	2.52E+10	10485312	9075312
14900000000	21900000000	612200000	2136193000	1.79E+08	1.18E+10	10943469	9383469
19400000000	22300000000	-9651000000	1115723200	1.73E+08	-1.7E+08	11441236	9681236
21100000000	22500000000	-1.386E+10	260597600	1.84E+08	-6.1E+09	10800801	8920801
0	0	29550000000	5682942500	6.73E+08	4.76E+10	9806726	7160726
0	0	32200000000	4135005000	8.7E+08	5E+10	10300588	7867588
168000	702000	38370000000	1163470000	1.53E+09	5.46E+10	10758180	8591180
35400000	256000000	43570000000	1369095600	1.8E+09	5.99E+10	10786199	8836199
380000000	2620000000	45130000000	869293100	1.45E+09	5.99E+10	10679969	8778969
1600000000	10100000000	42910000000	316773000	9.49E+08	5.53E+10	9834250	7960250
4070000000	18500000000	36200000000	967689900	5.23E+08	4.8E+10	9523839	7889839
6500000000	22700000000	28510000000	973003200	2.88E+08	3.97E+10	9744845	8262845
8380000000	23300000000	22990000000	663049400	1.94E+08	3.32E+10	9723995	8256995
10100000000	22800000000	16910000000	260311100	1.87E+08	2.59E+10	9464186	7939186
10800000000	22800000000	15840000000	16737200	2.06E+08	2.35E+10	8828340	7265340
0	0	29550000000	5682942500	6.73E+08	4.76E+10	9806726	7160726
0	0	32200000000	4135005000	8.7E+08	5E+10	10300588	7867588
168000	702000	38370000000	1181359500	1.57E+09	5.47E+10	10758180	8591180
5960000	132000000	46480000000	1355990100	2.25E+09	6.42E+10	11101755	8981755
55300000	1570000000	53380000000	1135741600	2.38E+09	7.12E+10	11339988	9199988
219000000	7460000000	58060000000	111771300	2.4E+09	7.41E+10	10537639	8379639
513000000	17000000000	58930000000	6160700	2.33E+09	7.38E+10	10118517	8046517
910000000	22800000000	55220000000	81195200	2.46E+09	6.92E+10	9713114	7736114

1420000000	24000000000	50330000000	210237300	1.63E+09	6.23E+10	9330693	7403693
2100000000	23800000000	44090000000	941111100	8.34E+08	5.39E+10	8630530	6760530
2810000000	23800000000	40980000000	-20562300	8.47E+08	4.96E+10	7872276	6072276
0	0	29550000000	5732640500	6.73E+08	4.76E+10	9813947	7167947
0	0	32200000000	4171124600	8.78E+08	5E+10	10277903	7844903
0	0	39550000000	5062389300	1.73E+09	6.04E+10	11994362	9364362
0	0	51160000000	5566452000	2.5E+09	7.53E+10	12889186	10149186
0	0	65840000000	4025617000	2.89E+09	9.14E+10	13578425	10648425
0	0	82130000000	2306466100	3.44E+09	1.08E+11	13317114	10177114
0	0	1.012E+11	150416400	4.1E+09	1.26E+11	13529877	10409877
0	0	1.177E+11	-238674100	4.83E+09	1.43E+11	13484531	10344531
0	0	1.296E+11	-147852200	5.11E+09	1.55E+11	13483656	10163656
0	0	1.309E+11	-495368200	4.96E+09	1.54E+11	13225089	9775089
0	0	1.276E+11	-1.53E+09	4.7E+09	1.49E+11	12723682	9243682

Ammonia emissions	NOx emissions	Organic carbon emissions	Sulfur emissions	VOC emissions	Freight transport energy	Passenger transport energy	Final energy	Final energy (electricity)	Final energy (gases)
57252530	1.33E+08	34307961	1.17E+08	1.56E+08	23586.44	51535.72	94659.94	14858.6	14632.81
63370296	1.33E+08	36628929	1.2E+08	1.61E+08	24706.31	52415	102022.6	17600.12	15088.05
65452771	1.12E+08	29281071	77310097	1.19E+08	31615.94	68243.55	96283.46	20475.07	16039.61
64920241	62378103	19670691	33131302	73392567	33417.13	68646.8	76348.26	19542.79	15204.95
65249185	46320523	19580160	18772619	76607723	41927.66	88176.82	80272.37	23141.35	15747.12
64527895	36245009	15823020	15778996	80854920	48817.4	106733.8	89059.29	30641.08	15049.48
63767207	33596395	15123670	14515230	83718705	54692.62	120896	95645.38	37951.31	13186.74
63494497	32540362	14640320	13013372	76982286	59254.58	131040.6	100209.5	43505.45	10885.3
63336046	30991118	13917360	10974212	60431515	62292.56	137685.2	101952.5	46522.01	8630.86
62943553	29108899	13006560	8707670	44897979	64143.62	140115.9	101123.5	47118.15	7354.334
62757524	28354803	12274840	6544224	33902567	65302.4	138994.6	98795.75	45633.04	6714.7
57252530	1.33E+08	34307961	1.17E+08	1.56E+08	23586.44	51535.72	94659.94	14858.6	14632.81
63370296	1.33E+08	36628929	1.2E+08	1.61E+08	24706.3	52415	102022.5	17600.12	15088.04
65458926	1.24E+08	29974100	92217560	1.29E+08	32350.74	69550.39	107002.5	22776.54	18417.54
64550449	91244644	20448059	51781521	93529834	39975.9	87041.42	110755	28327.47	23071.78
64046095	78481323	18729111	34236938	96492814	47462.24	104368.6	115322.2	33304.81	27958.41
63919444	63132701	17063910	24878540	1.03E+08	53708.36	118513.3	118909.4	37998.11	29122.11
63100295	56529266	16008030	20117041	1.06E+08	58802.96	129721.4	123071.6	43596.95	27758.91
62970935	49586587	16021749	16614031	94495153	62676.46	137779.2	122295.9	47413.73	24164.74
63262780	40977950	15224790	12700078	71209128	65360.46	142016.4	118157.4	49492.98	18862.07
63821339	36089663	14762580	9756788	52171577	67435.57	143146.7	115136.3	49645.6	14644.86
62568349	32438861	12643560	7383750	38393875	67079.69	140685.4	115780.5	53329.99	13755.99
57252530	1.33E+08	34307961	1.17E+08	1.56E+08	23586.44	51535.72	94659.94	14858.6	14632.81
63370296	1.33E+08	36628929	1.2E+08	1.61E+08	24706.3	52415	102022.5	17600.12	15088.04
65520294	1.26E+08	30174271	95622780	1.31E+08	32481.98	69769.05	109755.1	23377.29	18959.58
64974828	98959306	21692101	61189461	1.01E+08	40423.25	87962.43	119694.2	30677.19	25216.47
64492434	90786752	20089540	49187481	1.09E+08	48334.61	106415.7	131117.5	37969.53	32381.58
64058055	74827147	17549589	37063622	1.18E+08	54748.36	121437.7	140196.6	44335.17	35513.36
63056418	66913640	16557261	29915880	1.22E+08	59637.85	132831.4	145207.5	50130.07	35455.67
62496617	56615356	15924560	22333780	1.08E+08	62963.59	140145.9	141900.9	53482.63	31213.8
62231384	45110950	15013320	15266986	79972764	64871.04	143574.4	132101.5	54597.9	23939.9
62950149	37872851	14343660	10582134	56920318	66684.02	143852.4	123895.5	53973.02	16058.9
63693268	34950701	14584560	7790372	43016641	67014.65	141101.3	120611.1	54556.77	12337.23
57252530	1.33E+08	34307961	1.17E+08	1.56E+08	23586.44	51535.72	94659.94	14858.6	14632.81
63370296	1.33E+08	36628929	1.2E+08	1.61E+08	24706.3	52415	102022.5	17600.12	15088.04
65725726	1.27E+08	30750540	95745659	1.32E+08	32489.09	69774.67	109744.3	23408.55	18852.5
65550721	1.01E+08	23389009	63506741	1.04E+08	40499.54	88084.35	121362.8	31120.41	25716.46

65022605	97138591	21508751	58428501	1.15E+08	48581.52	106896.7	137205.5	39774.45	34343.5
64397584	84188545	18172899	53150921	1.26E+08	55153.21	122268.5	150270.2	47613.12	38281.28
63110841	76333484	16355860	45285702	1.3E+08	60158.14	133891.7	157331.4	54619.82	39255.53
62486892	65074061	15682000	34398121	1.16E+08	63684.91	141450.1	156565.2	59165.46	36450.33
62148963	50963826	14902050	23519899	88201717	65473.13	144820	149285.3	61707.27	31419.8
61770513	39635110	13914040	14746346	63454505	66243.93	144604	138859.1	62168.6	24951.27
60931843	32617609	12258870	9688266	45158742	66217.85	141534.4	130142.7	61799.75	19391.44
57252530	1.33E+08	34307961	1.17E+08	1.56E+08	23586.44	51535.72	94659.94	14858.6	14632.81
63370296	1.33E+08	36628929	1.2E+08	1.61E+08	24706.3	52415	102022.5	17600.12	15088.04
65915706	1.27E+08	31225559	95878540	1.33E+08	32493.46	69777.97	109794	23418.94	18869.04
66816046	1.04E+08	27416611	64427422	1.1E+08	40513.88	88103.35	121699	31192.39	25602.83
66041586	99984813	24607969	60487122	1.2E+08	48650.55	107025.5	138926.4	40269.2	34794
64791848	86621157	19053640	56424320	1.29E+08	55227.02	122425.2	152111.1	48279.37	39286.62
63130712	80452327	16092541	53727020	1.32E+08	60305.7	134154.8	161444.9	56139.49	40852.12
62523007	72084926	15416780	48621479	1.21E+08	63931.41	141883.8	165289.8	62528.64	39416.23
62164095	58645301	14677250	38789501	93792450	65965.62	145499.3	162777	67373.86	36026.22
61667248	46631548	13403940	28824760	67539198	66963.79	145521.6	156012.6	69612.22	31649.91
60712022	37471568	12041380	19804228	47907949	66733.94	142455.2	146752.7	69404.42	27420.28
53311985	1.18E+08	32788420	1.08E+08	1.92E+08			89745.07	15054.18	13385.57
55391244	1.12E+08	32779763	1E+08	1.88E+08			100480.9	17704.18	14593.62
49017490	1.04E+08	30234324	76406009	1.78E+08			121880.1	22761.13	15362.23
47190186	79802280	28237975	39257572	1.67E+08			117732.9	27124.47	15032.23
44647999	62598875	25958219	27407723	1.53E+08			116718.7	36957.53	19607.24
40612011	53912909	23561260	24649652	1.38E+08			121697.9	49233.65	27382.52
36762506	50982523	21056046	23015668	1.28E+08			131503.2	59522.83	30903.08
33839254	48509417	18509965	20838205	1.18E+08			140739.8	68928.94	29720.3
31744079	46160086	15928535	18938202	1.06E+08			150369.6	77530.06	28482.52
30264763	43669903	14011262	17201823	96324705			160087.9	85765.07	28383.91
29157855	41740367	13209558	16087878	92070142			171726.2	94928.13	30385.86
53311879	1.18E+08	32788517	1.08E+08	1.92E+08			89733.41	15054.18	13385.57
55391080	1.12E+08	32779506	1E+08	1.88E+08			100512.3	17704.18	14593.35
47446506	1.03E+08	30253298	76106893	1.78E+08			121818.4	22815.3	15148.07
48613481	90562273	28456995	54884506	1.72E+08			132648.4	28230.02	14999.73
48340300	76704356	26418585	35557614	1.62E+08			140093.2	34778.08	18632.24
46932245	65223686	24170570	26997506	1.47E+08			145913.5	44497.26	25524.19
44995728	60881793	21723496	25752987	1.35E+08			155615.1	55736.43	32853.08
41757230	58818169	19280390	25423773	1.22E+08			165121.2	68336.72	42996.42
38142461	55976980	16797840	24776132	1.12E+08			176510.7	79495.9	46069.76
35227297	52472877	14834049	22279189	1.02E+08			187570.7	90554.52	46498.09
32943961	48956111	13964566	19593698	96034253			201186.5	102640.4	48790.04
53311879	1.18E+08	32788517	1.08E+08	1.92E+08			89733.41	15054.18	13385.57
55391081	1.12E+08	32779500	1E+08	1.88E+08			100512.3	17704.18	14593.35
48538528	1.04E+08	30205917	76394847	1.78E+08			121829	22773.07	15547.23
51478546	98758745	28502199	65058482	1.74E+08			138625.4	28114.47	15868.35
52411875	86249560	26552324	49420869	1.67E+08			152290.4	34061.42	18700.57
51215310	77160040	24424562	39086969	1.56E+08			162528.2	41879.48	23675.85
49656583	68443039	22073453	32546421	1.41E+08			169619.9	52357.26	31235.86

47475218	63654822	19611427	27386266	1.29E+08	182018.2	61355.05	44325.87
45042846	59940277	17073827	25101105	1.15E+08	194610.4	72820.06	57093.1
42717643	57513421	15244832	25077999	1.07E+08	206192.1	86860.9	61043.94
39714351	54961487	14515687	24495394	1.04E+08	221311.6	100799.5	62219.22
53311879	1.18E+08	32788517	1.08E+08	1.92E+08	89733.41	15054.18	13385.57
55391078	1.12E+08	32779500	1E+08	1.88E+08	100512.3	17704.18	14593.35
48907312	1.04E+08	30183053	76779945	1.78E+08	122049	22733.63	15488.62
52915679	1.01E+08	28506840	72012877	1.75E+08	141517.3	28243.08	15528.07
55230967	90414941	26605900	59622242	1.68E+08	158485.7	34032.25	18074.74
55558188	83246750	24472385	48491201	1.59E+08	171562.4	41637.26	21857.8
54612257	76873134	22232003	42770105	1.46E+08	180952.9	51827.82	25827.24
52417313	71389706	19908906	38527958	1.34E+08	192411	61407.27	34360.03
49918622	66600884	17426649	34058628	1.21E+08	206954.1	69653.67	50415.04
47652420	61113035	15458670	28036548	1.09E+08	221569.1	79420.62	67280.61
45776741	58002888	14609433	24866807	1.03E+08	237571.9	92735.91	78309.23
53311879	1.18E+08	32788527	1.08E+08	1.92E+08	89733.41	15054.18	13385.57
55391081	1.12E+08	32779500	1E+08	1.88E+08	100512.3	17704.18	14593.35
49241564	1.04E+08	30197707	76941086	1.78E+08	122102	22733.63	15355.85
53855443	1.02E+08	28753617	77071207	1.75E+08	143212.9	28446.97	15426.68
57446165	94028460	26741032	68892340	1.69E+08	161666.2	34363.08	18080.29
60132049	88039094	24657581	59987498	1.61E+08	176647.1	41805.03	21503.35
61737246	83144982	22420164	55433520	1.49E+08	189505.2	52336.71	23460.57
60338393	77391872	20041463	49114445	1.38E+08	201934.3	63371.44	25856.41
58630678	74591867	17671837	45855792	1.31E+08	219801.6	71919.78	27739.74
57401985	71245470	15869921	42844127	1.26E+08	239946.9	79891.45	27687.24
55790124	67281343	15095103	38963058	1.23E+08	261107.7	89140.9	29776.97
53311876	1.18E+08	32788520	1.08E+08	1.92E+08	89732.57	15054.18	13385.57
55391055	1.12E+08	32779484	1E+08	1.88E+08	100512.3	17704.18	14593.35
50094262	1.04E+08	30278136	77969162	1.78E+08	122313.4	22744.74	15444.73
54419642	1.03E+08	28686193	79198786	1.75E+08	144246.5	28622.52	15585.57
57800607	95724742	26795279	72288668	1.69E+08	163101.8	34383.36	18290.01
60676602	90067498	24789173	65157221	1.61E+08	178869.9	41843.37	21045.02
62749454	85687352	22617675	61169703	1.51E+08	192858.2	52368.93	22503.07
63778857	80530130	20294772	56309629	1.4E+08	207202.9	64114.77	23571.96
63859411	78658440	17954287	52964512	1.33E+08	226423.8	72892.28	24515.02
64738704	76236743	16175726	48530784	1.29E+08	247655.5	81091.45	24571.69
65407187	72884597	15470049	43897887	1.27E+08	270511.9	91264.24	24693.91
52609600	1.23E+08	38066200	1.19E+08	2.1E+08	92822.52	15178.76	14949.96
53595900	1.16E+08	36648800	99761100	2.06E+08	100320.3	17068.46	16076.65
55837600	1.24E+08	36374300	1.03E+08	2.12E+08	122808.3	21168.18	20660.18
58200800	1.22E+08	35672600	97845100	2.11E+08	139833.6	25029.41	24878.27
58128100	84629400	31637800	55125400	1.94E+08	128419.6	27222.02	21236.24
58341600	75016500	30100700	43142000	1.91E+08	133181.1	32009.75	21316.68
58546400	69024900	28433500	35947700	1.85E+08	137015.1	37609.64	20945.74
57819500	62548700	26883100	30470400	1.76E+08	137568.9	44921.87	17997.38
57460300	57834500	25676200	26245000	1.68E+08	139328.4	52383.65	15229.76
57356100	54710500	24636400	22875100	1.6E+08	143110.5	60499.02	12845.45

57507800	53184300	23739700	20256000	1.53E+08						149298.1	68868.86	11055.18
52609600	1.23E+08	38066200	1.19E+08	2.1E+08						92822.52	15178.76	14949.96
53595900	1.16E+08	36648800	99761100	2.06E+08						100320.3	17068.46	16076.65
55837600	1.24E+08	36374300	1.03E+08	2.12E+08						122808.3	21168.18	20660.18
58248700	1.25E+08	35727000	1E+08	2.12E+08						143372.9	25601.91	25617.02
59109100	1.03E+08	32763100	72692800	2.01E+08						143206.4	27329.66	26629.88
59547900	91637600	30944900	58983900	1.97E+08						147128.4	29761.13	28493.69
59223100	78480900	28645700	43693800	1.89E+08						146801.5	34978.08	27399.88
59524000	74503800	27185500	37680300	1.83E+08						151240.1	38595.81	28200.44
59645300	71212000	25812900	33973600	1.76E+08						155017.3	43532.09	27915.55
59688200	67368900	24554500	29944000	1.69E+08						158460	49708.87	26199.24
59570600	63252300	23419300	25745100	1.61E+08						161540.5	57455.63	22983.3
52609600	1.23E+08	38066200	1.19E+08	2.1E+08						92822.52	15178.76	14949.96
53595900	1.16E+08	36648800	99761100	2.06E+08						100320.3	17068.46	16076.65
55837600	1.24E+08	36374300	1.03E+08	2.12E+08						122808.3	21168.18	20660.18
58252900	1.25E+08	35732800	1.01E+08	2.12E+08						143649.5	25683.58	25637.99
59506700	1.12E+08	33483000	82974200	2.05E+08						149753.6	28275.3	28278.52
60232900	1.06E+08	31824000	74715900	2.02E+08						156329.5	30941.14	31356.97
60712800	1.03E+08	30120300	70425800	1.97E+08						164031.6	33647.83	35891.67
60723500	96056400	28190600	61024800	1.9E+08						168505	35874.72	38691.56
61023800	89474000	26447600	52701200	1.84E+08						172716.4	38963.86	40542.45
61625200	85773000	24998000	46939700	1.78E+08						179838.7	43278.06	42581.53
62145300	83214300	23602600	42348100	1.72E+08						187754.9	48715.62	44083.67
52609600	1.23E+08	38066200	1.19E+08	2.1E+08						92822.52	15178.76	14949.96
53601600	1.17E+08	36655400	1E+08	2.06E+08						100497.1	17064.6	16088.96
55882500	1.29E+08	36445300	1.07E+08	2.12E+08						124576.8	21593.43	20729.27
58365700	1.33E+08	35836900	1.07E+08	2.14E+08						146030	26786.08	25797.47
60405900	1.35E+08	35204500	1.07E+08	2.12E+08						161166.6	31701.41	29765.47
61905000	1.36E+08	33860900	1.06E+08	2.12E+08						172053.1	37178.36	33548.42
62862300	1.33E+08	32100900	1.02E+08	2.08E+08						180299.3	41435.34	37965.09
63575200	1.3E+08	30451900	98786500	2.03E+08						188529.4	45668.59	41383.45
64319100	1.26E+08	28853900	95054400	1.98E+08						196848.6	50095.6	44652.34
65200300	1.23E+08	27370500	89455300	1.93E+08						206498.9	54668.4	47816.12
66126900	1.19E+08	25897700	82541000	1.88E+08						216383.2	59620.3	51081.6

52338447	1.09E+08	36065237	1E+08	1.54E+08	27877.41	63560.13	109403.3	18254.26	17649.46			
61761490	1.11E+08	31858344	96043410	1.7E+08	39066.31	77057.51	131621.5	25795.87	19939.02			
68042818	82431063	32820865	55153636	1.59E+08	47765.41	87313.47	138656.3	36620.52	19956.54			
73237931	67842202	33672877	38644663	1.57E+08	56267.85	95279.86	148863.3	47299.79	20136.4			
77084917	59648453	34710961	30907309	1.58E+08	61922.93	99909.97	154096.1	57885.04	18786.45			
79766916	51747872	32744791	26126558	1.51E+08	64986.83	101862.5	156283.4	67181.41	16914.93			
81349299	44730093	29869102	23140201	1.41E+08	66671.15	101693.2	156989.9	75007.42	14876.13			
80324017	34085085	22632578	20362663	1.2E+08	66968.51	100026.2	156418.1	81090.15	12855.88			
76576647	25777406	18172266	18908764	1.04E+08	66885.15	97310.17	155947	86297.02	10970.26			
74157414	19729080	14907335	18729518	94551638	67462.36	93697.56	158428.9	92748.88	9322.643			

52338447	1.09E+08	36065238	1E+08	1.54E+08	27877.41	63547.16	109403.3	18254.26	17649.46			
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61761490	1.11E+08	31858335	96043408	1.7E+08	39031.56	77082.48	131621.5	25795.87	19939.02
68518057	98721750	31852399	75661714	1.67E+08	49498.26	88249.5	145305.9	33867.23	22190.13
73786023	82929168	32075639	57008450	1.63E+08	58859.77	96825.54	156947.6	42658.74	23368.08
78076765	67333385	31355405	40527236	1.58E+08	65456.52	102210.6	162676.8	51591.64	22963.95
80836913	58193482	29820286	32174753	1.53E+08	69532.36	105148.2	164745.6	59947.97	21688.17
82943288	51205066	29906055	27248226	1.48E+08	72196.93	105990.6	164880.8	68327.58	19500.49
84209784	42535393	28338574	23427843	1.35E+08	72702.85	104808.7	163116.5	75287.2	17055.27
83300739	33584273	22712575	20888418	1.18E+08	72077.69	102329.8	160787.2	80691.22	14725.75
79757822	25706578	18095963	19373512	1.03E+08	71075.36	98815.94	159297.2	85531.99	12585.33

52338447	1.09E+08	36065238	1E+08	1.54E+08	27877.41	63547.16	109403.3	18254.26	17649.46
61761490	1.11E+08	31858335	96043408	1.7E+08	39031.56	77082.48	131621.5	25795.87	19939.02
68674078	1.04E+08	31412794	83522583	1.7E+08	50385.22	88700.69	148826.6	33075.88	23097.53
74228884	93730475	31397276	70266339	1.68E+08	60266.49	97548.41	161760.2	40771.17	24761.04
78753749	77965238	30308028	53429290	1.62E+08	67545.8	103315.7	168421.5	48267.86	25092.57
81508865	64708808	28272231	39815118	1.56E+08	72320.14	106789.4	171091	55348.44	24486.98
83768680	55675915	27485530	31560889	1.5E+08	75638.88	108247.3	171130.5	62958.68	22824.02
86251542	47002587	19467821	28459254	1.33E+08	79792.86	109631.6	173905.4	65682.64	23715.11
87771081	42475451	17910126	26719114	1.27E+08	83114.09	109935.1	174765.3	68163.62	23971.76
88838694	37930150	18473316	24626494	1.22E+08	84636.43	108844.6	173422.1	71577.39	23068.13

52338447	1.09E+08	36065238	1E+08	1.54E+08	27877.41	63547.16	109403.3	18254.26	17649.46
61761490	1.11E+08	31858335	96043408	1.7E+08	39031.56	77082.48	131621.5	25795.87	19939.02
68967840	1.1E+08	30892323	95051686	1.75E+08	51860.54	89365.2	154709.5	32885.9	23903.43
74676335	1.06E+08	30191319	89050302	1.76E+08	62697.15	98619.77	170470.1	39314.15	26239.07
79766105	97735576	29073850	80247739	1.74E+08	71370.58	104969.3	180331.2	44610.21	27622.8
83509746	90131870	26596503	72113049	1.71E+08	78104.83	109392.2	186468.1	48658.58	28510.69
86712501	81759932	24382476	62772873	1.65E+08	83766.57	112150.8	189528.6	52402.04	28901.38
89086445	67996945	21536499	49556399	1.53E+08	87630.64	113322.5	189441	55651.32	28818.69
89812289	57016247	19369327	39435531	1.41E+08	90254.04	113312.5	187402.9	59112.25	28415.3
90698042	47827677	18416347	32109073	1.31E+08	91603.71	112371.7	184553.6	62943.39	27795.91
46905961	1.12E+08	31285759	1.15E+08	1.55E+08	24644.52	53575.07	99737.11	15448.36	16015.22
52338447	1.09E+08	36065238	1E+08	1.54E+08	27877.41	63547.16	109403.3	18254.26	17649.46
61922658	1.13E+08	32187336	1E+08	1.73E+08	39505.89	77438.25	133627.9	26010.95	20478.81
69229225	1.13E+08	31316550	97979371	1.78E+08	52215.92	89510.29	155595.3	33166.02	23795.49
75042748	1.09E+08	30316383	93226039	1.79E+08	63284.48	98846.35	171863.1	39550.5	26168.08
80202546	1.02E+08	28603453	85534953	1.77E+08	72257.67	105288.1	182339.9	44761.42	27627.45
84079084	95453395	26590607	78806001	1.76E+08	79409.05	109857.4	189465.7	48456.42	28703.58
87793320	88151967	24242515	70946165	1.72E+08	85700.58	112834.6	193890.8	51643.71	29390.53
89826772	75915997	21255378	59432918	1.59E+08	90530.3	114350.8	195636.4	53872.95	29785.16
91577125	67313124	18919223	51448342	1.51E+08	94593.49	114865.3	196032.1	55663.28	30198.43
93354460	59735820	16786883	44291864	1.44E+08	98049.37	114752.1	196325.4	57118.9	30833.91
39337300	1.17E+08	29106100	1.14E+08	1.55E+08	85050	38050	91861.18	14861.12	14252.79
42243600	1.11E+08	27760700	94597200	1.52E+08	93100	41740	99000.08	17491.68	15766.68
49795600	1.13E+08	26096300	74469400	1.52E+08	134600	65450	125222.3	24369.46	20363.91
56015700	92643000	23067100	48171800	1.39E+08	167900	89580	137139	28944.47	14322.23
65023500	66677200	19562300	29076200	1.19E+08	162400	94110	132805.7	40138.92	10188.9

73552900	46048400	17471300	18508800	1.01E+08	162800	108100	142166.8	64638.94	7825.006
81449100	40572700	16579500	14767800	90694700	130700	133200	150277.9	89388.96	5988.894
86182200	38863100	15974300	13913200	86309100	120200	156600	170805.7	109611.2	5830.56
86967400	37946700	15615300	13672700	82635300	124100	187500	191166.8	126305.7	6244.449
87669100	35777500	15155300	13045900	78748400	125000	208500	209805.7	143500.1	6350.005
86862800	33145500	14853400	11879900	74809200	127400	237400	224694.6	156777.9	6202.783
39271500	1.17E+08	28982600	1.14E+08	1.55E+08	85050	38050	91861.18	14861.12	14252.79
42481200	1.11E+08	28399200	94702800	1.53E+08	93100	41740	99000.08	17491.68	15766.68
49648400	1.14E+08	26350000	74507300	1.52E+08	134600	65450	125222.3	24369.46	20363.91
55902200	99143900	23292100	50752200	1.4E+08	179600	94300	149694.6	32583.36	18972.24
60683500	78595200	20285200	34264100	1.25E+08	199000	108600	160722.4	42750.03	17494.46
67873100	55079600	18291700	22473200	1.12E+08	218800	126800	172777.9	59277.83	17522.24
77841500	48620200	17207900	16864100	98930600	223200	142000	175611.3	78972.29	15538.9
82780000	42591600	16573500	13399700	88636600	208000	159400	184833.5	100555.6	15194.46
85816600	37860300	16015900	11557200	83560300	183500	188600	198750.2	118527.9	13430.57
88170700	36005900	15668700	11943300	79408800	169500	203500	214250.2	137250.1	9677.786
87410300	34524900	15287800	12248000	75404200	163900	237000	229778	151194.6	9063.896
39271500	1.17E+08	28982600	1.14E+08	1.55E+08	85050	38050	91861.18	14861.12	14252.79
42481200	1.11E+08	28399200	94702800	1.53E+08	93100	41740	99000.08	17491.68	15766.68
49648400	1.14E+08	26350000	74514300	1.52E+08	134600	65450	125222.3	24369.46	20363.91
55669000	1.01E+08	23468400	53476100	1.4E+08	178500	94340	151166.8	34083.36	20619.46
59920100	83410200	20536300	36908700	1.27E+08	202900	110900	168666.8	44750.04	22227.8
63119000	59973200	18854100	25382000	1.15E+08	235200	133200	186944.6	59916.71	23619.46
69928100	54135000	17920400	19880600	1.05E+08	256700	151200	194694.6	75694.51	24008.35
75658900	47191200	17113500	15276500	92649600	250100	165700	199000.2	92305.63	26516.69
80005200	41027500	16437600	12135900	84649700	236000	193900	209333.5	112694.5	23600.02
83506300	36461100	16009700	10915600	79998600	218000	209400	221722.4	130833.4	17141.68
84517400	33119600	15641500	10102700	75947300	200800	236500	232861.3	144666.8	13152.79
39271500	1.17E+08	28982600	1.14E+08	1.55E+08	85050	38050	91861.18	14861.12	14252.79
42481200	1.11E+08	28399200	94702800	1.53E+08	93100	41740	99000.08	17491.68	15766.68
49648400	1.14E+08	26350000	74514300	1.52E+08	134600	65450	125222.3	24369.46	20363.91
55740300	1.02E+08	23546900	55425900	1.41E+08	179100	94590	152083.5	34305.58	20625.02
59923500	86381900	20734500	39816900	1.27E+08	205400	112200	173055.7	45055.59	23613.91
63321100	65216100	19062100	28100500	1.17E+08	242800	136800	196444.6	59388.94	27319.47
68969200	60091300	18290400	23111200	1.09E+08	276000	158000	210666.8	73055.61	29916.69
72888500	53993800	17588600	18558000	98530900	289500	173000	218750.2	87027.85	36194.47
74318900	48690000	17063000	15249400	89284200	311700	203900	233166.9	103305.6	39527.81
74962700	42480700	16506800	13220100	82409100	313900	223700	243861.3	118333.4	36861.14
73470300	37798900	16104100	11467400	77177000	330200	254700	258028	127722.3	40861.14
39271500	1.17E+08	28982600	1.14E+08	1.55E+08	85050	38050	91861.18	14861.12	14252.79
42481200	1.11E+08	28389200	94700800	1.53E+08	93100	41740	99000.08	17491.68	15766.68
49648400	1.14E+08	26350000	74508300	1.52E+08	134600	65450	125222.3	24369.46	20363.91
56245600	1.06E+08	23754000	60934900	1.41E+08	182600	95850	156166.8	35361.14	21933.35
59740000	94948700	21055700	50130800	1.29E+08	215500	116000	184666.8	47555.59	27236.13
62091800	75617100	19450000	36751700	1.2E+08	258600	143500	213222.4	60944.49	32444.47
65603700	72420800	18790000	29266700	1.15E+08	300400	167700	233722.4	70527.83	39000.03
67951500	65562600	18206100	23190700	1.06E+08	327000	183200	248028	80083.4	50361.15

68859500	58446200	17754700	18754200	97114100	364000	212600	261333.5	92972.3	56166.71
68540500	50456300	17305700	15771500	88150500	375000	231700	268472.4	108111.2	56638.93
66432700	43611100	16815600	13043000	81580700	387600	261500	279722.4	117777.9	63388.94
39337300	1.17E+08	29106100	1.14E+08	1.55E+08	85050	38050	91861.18	14861.12	14252.79
42243600	1.11E+08	27750700	94595200	1.52E+08	93100	41740	99000.08	17491.68	15766.68
49875500	1.17E+08	28145500	77239400	1.55E+08	135200	65570	125139	24908.35	18850.02
56405400	1.12E+08	25552200	65961300	1.44E+08	185800	96860	159805.7	35638.92	23175.02
60553900	1.05E+08	22302700	59927800	1.31E+08	225700	119500	197805.7	49583.37	34777.81
62747700	88065700	20332500	48566900	1.22E+08	274700	149700	232694.6	64861.16	42611.15
66896100	89181400	19431200	41758000	1.18E+08	328100	178700	261222.4	76138.95	50777.82
70696500	87537900	18737400	35218700	1.12E+08	368100	199300	285000.2	85750.07	61250.05
71354400	83521000	18304000	29339400	1.06E+08	425800	232200	307778	95694.52	66694.5
71355700	74865000	17733200	24667800	97176700	460700	250700	316944.7	105972.3	68166.72
69138500	63535500	17142000	18952800	87767600	485100	280100	324166.9	114416.8	75388.95

Final energy (heat)	Final energy (hydrogen)	Final energy (industry)	Final energy (liquids)	Final energy (residential/commercial)	Final energy (solids)	Final energy (traditional biomass)	Final energy (transport)	Radiative forcing	Radiative forcing (aerosols)
3680.478	1.91E-06	28803.27	42149.23	32357.69	19338.83	10553.69	25079.37	1.870916	-1.11517
4083.709	0.10653	33812.83	42081.13	34022.74	23169.45	11266.13	24831.47	2.139458	-1.05053
3242.755	5.545885	32795.05	38729.98	30646.3	17790.49	5952.919	26012.24	2.582151	-0.88032
2030.806	2920.313	29913.39	22333.99	25876.74	14315.43	2981.283	17312.28	2.843904	-0.58559
1568.672	11819.6	31243.19	16198.48	27875.26	11797.13	2594.487	18288.08	2.791113	-0.48819
1401.934	15181.73	33728.69	14899.71	31751.84	11885.36	2290.657	19828.87	2.634877	-0.43835
1141.998	14935.96	35460.36	14791.12	35792.93	13638.25	1829.056	20318.33	2.469284	-0.42607
869.194	15211.33	35100.03	15143.24	39596	14594.96	1358.427	21380.41	2.336205	-0.41347
659.2483	16528.12	33468.11	14807.99	41591.39	14804.27	1036.26	22776.23	2.207992	-0.39178
481.8698	18754.32	30800.33	13741.91	42016.77	13672.91	735.7428	24254.54	2.068866	-0.36447
347.792	21858.62	27815.36	12478.16	41740.91	11763.46	446.8262	25411.49	1.905195	-0.34318
3680.478	1.91E-06	28803.27	42149.23	32357.69	19338.83	10553.69	25079.37	1.870916	-1.11517
4083.709	0.10653	33812.8	42081.13	34022.74	23169.43	11266.13	24831.47	2.135342	-1.05491
3732.17	4.049789	37248.45	42367.76	33462.53	19704.46	6417.03	28436.91	2.551068	-0.97582
3080.014	259.9785	39031.26	38356.62	35255.77	17659.14	3881.47	29422.52	2.931325	-0.7469
2463.71	879.2871	40590.61	33608.79	38006.7	17107.16	3474.336	31073.05	3.092123	-0.63699
2016.901	1229.747	40659.84	32251.64	40527.23	16290.89	2877.05	31288.22	3.124641	-0.55117
1529.622	2453.096	40877.56	31404.78	44107.35	16328.2	2267.683	31515.69	3.089988	-0.5054
1112.317	5111.401	38593.48	28946.26	46223.52	15547.47	1702.658	30962.47	3.024207	-0.47206
788.4087	12046.53	35338.81	22805.51	46370.19	14161.89	1261.484	30443.64	2.916334	-0.43055
573.5718	18890.22	31727.11	19011.63	46759.32	12370.47	877.8849	30899.8	2.769267	-0.39889
419.0526	18759.15	29105.64	19098.8	49642.17	10417.45	549.7346	30677.25	2.637267	-0.36004
3680.478	1.91E-06	28803.27	42149.23	32357.69	19338.83	10553.69	25079.37	1.870916	-1.11517
4083.709	0.10653	33812.8	42081.13	34022.74	23169.43	11266.13	24831.47	2.1344	-1.05592
3840.475	4.39467	38421.81	43353.23	34113.16	20220.1	6524.672	29090.5	2.568914	-0.99923
3373.128	260.7912	42617.23	40979.18	38009.59	19187.46	4207.931	31325.72	3.006489	-0.82262
2937.68	835.4843	45951.07	37768.45	43234.41	19224.79	3976.664	34612.11	3.270402	-0.75556
2494.568	943.6385	47432.62	37843.87	47632.21	19066.05	3418.961	36455.45	3.47776	-0.65081
1886.552	1505.033	47529.84	37339.03	51815.57	18891.19	2730.274	37286.11	3.602119	-0.58833
1328.265	2560.994	44643.73	35176.21	53267.49	18138.98	2036.958	36146.5	3.676591	-0.51882
904.3152	5693.841	39366.2	30215.88	52415.58	16749.67	1462.251	33515.64	3.660825	-0.45007
621.8869	13022.6	34508.28	24593.97	51103.74	15625.09	967.5258	32313.42	3.54306	-0.40562
450.7676	17667.53	30829.44	21880.4	51465.45	13718.4	563.2296	32400.11	3.383062	-0.3867
3680.478	1.91E-06	28803.27	42149.23	32357.69	19338.83	10553.69	25079.37	1.870916	-1.11517
4083.709	0.10653	33812.8	42081.13	34022.74	23169.43	11266.13	24831.47	2.13433	-1.05603
3840.792	4.395865	38428.39	43405.54	34080.27	20232.48	6525.575	29101.83	2.571433	-1.00275
3423.795	254.4227	43188.42	41593.97	38478.53	19253.75	4279.289	31705.58	3.021749	-0.84861

3095.419	840.0762	48082.9	39503.18	45199.08	19648.91	4186.184	35929.75	3.320321	-0.83175
2694.688	948.1271	51315.62	40261.71	51020.33	20471.27	3688.761	38640.33	3.597944	-0.77368
2055.109	1388.148	51391.76	39980.12	56265.3	20032.67	2989.461	39963.01	3.858525	-0.70532
1481.636	2210.044	48793.73	38178.37	59033.44	19079.31	2290.96	39437.81	4.079861	-0.61379
1039.058	3266.039	44392.28	34012.86	59442.94	17840.32	1721.051	37021.64	4.209114	-0.51556
705.6778	4444.017	39374.03	29997.59	57958.49	16591.9	1168.176	34088.28	4.268145	-0.42964
472.2423	6064.555	34688.28	27103.7	56366.41	15310.97	669.982	32327.47	4.270901	-0.3703
3680.478	1.91E-06	28803.27	42149.23	32357.69	19338.83	10553.69	25079.37	1.870916	-1.11517
4083.709	0.10653	33812.8	42081.13	34022.74	23169.43	11266.13	24831.47	2.134266	-1.05613
3841.55	4.399876	38440.23	43429.95	34094.98	20230.12	6526.647	29118.3	2.576915	-1.00585
3435.272	253.9158	43551.59	41600.03	38557.72	19614.6	4274.045	31766.05	3.067757	-0.87126
3143.208	846.7329	48861.82	39838.46	45716.08	20034.82	4230.42	36300.61	3.450918	-0.85968
2734.426	952.8746	51461.07	40798.21	51685.44	20059.62	3744.603	39070.92	3.798741	-0.80384
2112.892	1396.559	52752.52	40840.25	57722.52	20103.6	3068.519	40884.84	4.089258	-0.76863
1566.54	2291.281	51652.88	39740.05	62286.05	19747.01	2419.758	41255.51	4.366412	-0.72084
1128.275	3519.517	48529.74	35751.97	64888.58	18977.21	1892.147	39685.37	4.622711	-0.63436
786.5912	4903.179	44154.2	31610.84	65223.75	17449.83	1324.84	37484.06	4.833992	-0.54025
526.6532	6298.936	38979.34	28206.77	63725.27	14895.64	778.1809	35607.81	5.009074	-0.45371
3043.891	0	32468.36	39848.37	33208.36	18331.68	8144.729	24068.07	1.870916	-1.11517
3206.391	0	37503.36	41997.81	36444.47	22360.02	8473.062	26533.35	2.137667	-1.05306
3720.836	0	46014.76	53367.82	42347.81	24216.96	7867.229	33517.53	2.623028	-0.93934
5946.949	530.8338	42955.31	44118.09	41591.98	19800.85	7269.728	33185.58	2.997782	-0.70567
7112.783	1905.835	42669.48	28662.52	42681.15	14741.12	6240.838	31368.08	3.001046	-0.59917
6928.061	2638.613	45286.43	13303.07	45406.7	13131.95	5005.004	31004.75	2.847006	-0.55885
5710.282	4226.67	47681.15	11886.4	49307.26	9185.563	3635.836	34514.47	2.672744	-0.53856
5375.838	4564.448	49105.87	17363.63	54338.1	3928.892	2247.502	37295.86	2.487768	-0.51761
5936.671	4615.837	50878.93	20488.63	59796.99	2000.279	750.5562	39693.64	2.281985	-0.49729
6578.339	4625.559	52285.88	22081.68	66052.28	1240.834	0	41749.76	2.072509	-0.4793
7141.117	4238.892	54022.54	22305.02	73214.78	1246.945	0	44488.65	1.882197	-0.46397
3043.891	0	32456.97	39836.7	33208.36	18331.68	8144.729	24068.07	1.870916	-1.11517
3206.391	0	37509.75	42004.48	36469.2	22384.74	8473.062	26533.35	2.137809	-1.05292
3926.114	0	46119.2	53105.6	42290.31	24309.19	7867.229	33408.92	2.619799	-0.9414
5747.227	283.3336	48844.21	53207.82	46242.54	24669.19	7269.728	37561.7	3.004945	-0.80373
6845.839	1106.39	52017.26	50521.43	48697.54	19648.35	6240.838	39378.36	3.224943	-0.66835
8201.951	2470.002	55711.71	38828.36	52268.1	16048.35	5005.004	37933.36	3.249548	-0.59742
9402.785	3871.948	58009.21	29034.75	56959.77	13179.73	3635.836	40646.14	3.182839	-0.58372
8692.229	5047.782	59193.94	19546.4	61205.88	8130.284	2247.502	44721.7	3.081103	-0.57851
8903.896	5529.171	61501.99	16609.46	66329.78	6919.172	750.5562	48678.93	2.946145	-0.56444
8445.562	5469.171	62744.77	17797.51	72505.06	5556.393	0	52320.88	2.792915	-0.53943
8641.118	5435.282	64187	19117.24	80343.68	3090.836	0	56655.88	2.643176	-0.51119
3043.891	0	32456.97	39836.7	33208.36	18331.68	8144.729	24068.07	1.870916	-1.11517
3206.391	0	37509.75	42004.2	36469.2	22384.74	8473.062	26533.35	2.137674	-1.05305
3810.003	0	46055.59	53220.6	42279.76	24009.19	7867.229	33493.64	2.622219	-0.94735
5186.671	51.11115	51257.82	57441.99	47166.15	26573.91	7269.728	40201.42	3.02461	-0.87498
5782.227	353.6114	55947.27	58341.99	51116.15	26378.08	6240.838	45226.98	3.357604	-0.76014
6044.727	887.2229	60754.49	53971.43	55000.04	25233.63	5005.004	46773.65	3.533795	-0.68464
6444.727	2113.891	64994.22	43236.7	60364.77	21992.24	3635.836	44260.87	3.634248	-0.63276

8380.562	3533.614	67520.61	36400.03	66479.22	14908.35	2247.502	48018.37	3.673553	-0.59919
11433.34	4348.337	68437.83	27570.3	73263.67	7507.228	750.5562	52908.93	3.650251	-0.58042
12230.01	5557.782	69158.67	20659.18	79346.73	5596.949	0	57686.44	3.577758	-0.57019
12276.12	6303.338	71494.78	19265.85	86647.01	5862.782	0	63169.77	3.486103	-0.5531
3043.891	0	32456.97	39836.7	33208.36	18331.68	8144.729	24068.07	1.870916	-1.11517
3206.391	0	37509.75	42004.48	36469.2	22384.74	8473.062	26533.35	2.137552	-1.05317
3736.947	0	46134.2	53193.65	42396.98	24448.63	7867.229	33517.8	2.62302	-0.95176
5076.115	0	52752.82	57698.38	47921.15	29683.63	7269.728	40843.09	3.014606	-0.91873
4895.282	244.7224	58650.32	60561.72	52618.65	32125.86	6240.838	47216.7	3.394818	-0.8275
4881.671	447.7781	63993.66	59915.05	56920.05	31701.97	5005.004	50648.37	3.674516	-0.75301
5580.56	1561.39	69155.33	52582.54	62653.11	30912.8	3635.836	49144.48	3.89118	-0.70503
7414.45	2810.558	73558.95	43301.98	69062	29527.25	2247.502	49790.04	4.070099	-0.67132
9259.73	3662.781	75732.84	35413.08	76123.67	24261.13	750.5562	55097.82	4.202828	-0.63922
11259.73	5034.726	77219.51	27337.8	83875.9	16522.79	0	60473.66	4.272958	-0.59836
13450.29	6520.839	78401.73	22323.07	92553.96	9147.23	0	66616.16	4.280675	-0.57352
3043.891	0	32456.97	39836.7	33208.36	18331.68	8144.729	24068.07	1.870916	-1.11517
3206.391	0	37509.75	42004.2	36469.2	22384.74	8473.062	26533.35	2.137499	-1.05323
3697.781	0	46174.76	53297.26	42409.76	24570.58	7867.229	33517.8	2.623053	-0.95449
4490.281	0	53876.99	58480.88	48140.04	31065.3	7269.728	41195.87	3.010648	-0.95274
3947.781	148.3335	60285.33	61940.61	53316.99	34794.19	6240.838	48063.93	3.444984	-0.88809
3593.614	582.7782	66177	63063.94	58055.32	35313.08	5005.004	52414.76	3.843814	-0.82909
3746.67	915.2785	72733.11	58188.66	64732.55	37918.64	3635.836	52039.76	4.217579	-0.79107
5415.56	1620.001	77865.9	53309.76	71945.61	38260.59	2247.502	52122.82	4.579262	-0.74638
7643.339	2883.891	82848.4	57240.32	79387.01	37506.42	750.5562	57566.43	4.892227	-0.72265
10873.62	6001.116	87958.68	63363.94	88103.68	36701.97	0	63884.5	5.188424	-0.70114
12078.34	8383.618	92503.41	68263.39	97827.58	37581.42	0	70776.72	5.488135	-0.67303
3043.891	0	32455.86	39835.87	33208.36	18331.68	8144.729	24068.07	1.870916	-1.11517
3206.391	0	37509.75	42004.48	36469.2	22384.74	8473.062	26533.35	2.137271	-1.05348
3483.336	0	46305.04	52895.88	42489.48	25297.8	7867.229	33518.92	2.621972	-0.95996
3946.392	0	54548.38	58570.88	48318.65	32270.86	7269.728	41379.48	3.016565	-0.96481
3411.392	149.1668	61096.72	62748.94	53531.15	35879.47	6240.838	48473.93	3.469712	-0.91134
3177.78	585.2782	67383.11	64354.22	58375.6	37064.47	5005.004	53110.88	3.922371	-0.85972
3257.78	869.7229	74352.84	60428.1	65267	40495.03	3635.836	53238.38	4.394603	-0.82717
3838.336	1430.834	80741.18	55811.43	73488.95	44187.26	2247.502	52972.82	4.897461	-0.79114
5380.56	3290.558	86680.35	61531.16	81081.18	43771.7	750.5562	58662.55	5.421348	-0.77162
8679.174	6835.839	92354.52	69743.11	89548.13	41078.09	0	65752.83	5.982997	-0.74727
10266.95	8400.562	97734.8	76783.12	99807.3	42841.42	0	72969.78	6.560877	-0.71699
3071.919		35279.75	39557.2	34468	19847.21		23074.77	1.870916	-1.11517
3502.058		37264.2	42463.84	37604.42	20892.16		25451.69	2.133461	-1.05832
4376.67		44819.59	51740.46	45876.18	24281.96		32112.58	2.62038	-1.05672
5292.115		52027.96	56237.21	51622.24	27554.27		36183.42	3.144272	-1.00245
5787.477		47676.9	52596.88	49893.68	21246.74		30849.05	3.583005	-0.74743
6520.45		50103.54	50931.32	51445.18	22077.68		31632.41	3.654403	-0.65892
7079.006		52752.68	47797.73	52360.24	23263.82		31902.11	3.67028	-0.60667
7741.562		54299.74	42476.2	52339.99	24177.13		30929.19	3.671116	-0.5689
8327.146		56369.85	37699.97	52369.74	25481.44		30588.75	3.640354	-0.53959
8861.313		59243.16	33655.92	52726.71	27076.91		31140.66	3.588572	-0.51607

9404.146	63241.13	30782.3	53450.93	29041.16	32606	3.522411	-0.49848
3071.919	35279.75	39557.2	34468	19847.21	23074.77	1.870916	-1.11517
3502.058	37264.2	42463.84	37604.42	20892.16	25451.69	2.133461	-1.05832
4376.67	44819.59	51740.46	45876.18	24281.96	32112.58	2.624063	-1.05764
5293.976	52669.21	58051.44	52714.79	27905.22	37988.89	3.16509	-1.0252
5705.143	52872.13	58703.63	53846.4	24210.96	36487.92	3.63922	-0.85827
5874.727	55172.6	57557.41	54964.88	24809.41	36990.86	3.869095	-0.75849
6515.7	56265.82	52542.49	54840.57	24836.55	35695.06	4.0363	-0.65716
6789.117	59316.69	50846.01	55505.88	26291.83	36417.61	4.128543	-0.61656
7250.645	62322.55	47987.46	55979.71	27842.22	36715.08	4.204479	-0.59388
7804.923	65280.89	44866.65	56206.88	29444.94	36972.22	4.263437	-0.56796
8470.479	68181.47	41118.31	56142.32	31154.44	37216.75	4.293275	-0.54016
3071.919	35279.75	39557.2	34468	19847.21	23074.77	1.870916	-1.11517
3502.058	37264.2	42463.84	37604.42	20892.16	25451.69	2.133461	-1.05832
4376.67	44819.59	51740.46	45876.18	24281.96	32112.58	2.625554	-1.05774
5295.643	52721.88	58173.6	52794.29	27948.77	38133.34	3.17029	-1.03007
5784.449	55437.77	60203.6	55556.49	26378.58	38759.34	3.664934	-0.92088
5914.894	58832.13	59767.71	57419.21	27440.33	40078.12	3.988574	-0.86623
5889.394	63240.86	57883.96	59214.38	29644.5	41576.37	4.312689	-0.8375
5928.283	66394.55	56225.02	59911.71	30718.11	42198.76	4.660433	-0.77719
6123.977	69704.22	54062.35	60374.6	31987.97	42637.59	4.944131	-0.72588
6374.866	74349.25	52527.18	61409.24	34023.11	44080.23	5.183833	-0.6919
6837.45	79354.06	50493.98	62467.49	36556.58	45933.37	5.410145	-0.66614
3071.919	35279.75	39557.2	34468	19847.21	23074.77	1.870916	-1.11517
3501.225	37274.11	42567.4	37609.67	20955.74	25613.35	2.132032	-1.05977
4389.92	45014.45	52586.63	46178.43	24661.1	33383.89	2.617478	-1.08775
5359.699	53007.63	58899.3	53350.82	28228.8	39671.53	3.180898	-1.09001
6085.255	59226.52	61714.22	58106.77	30657.47	43833.31	3.758835	-1.07851
6498.477	64624.02	60672.72	61308.66	32673.03	46120.4	4.29286	-1.08097
6517.227	69276.81	58158.32	63412.75	34538.14	47609.7	4.839877	-1.06926
6520.005	74028.95	56349.66	65124.94	36746.61	49375.51	5.395268	-1.0574
6509.561	79029.29	54370.46	66698.86	39204.92	51120.46	5.961699	-1.04334
6496.7	84687.98	53227.38	68352.78	42125.76	53458.13	6.55243	-1.0171
6580.144	90537.04	51306.18	69938.06	45510.54	55908.07	7.165433	-0.98283

2701.973	0	48508.09	43841.42	33096.45	26956.14	8491.139	27346.69	2.135616	-1.05572
2767.583	92.31838	58485.16	51971.99	39927.69	31054.68	9495.258	32646.98	2.615401	-0.99488
1739.217	309.2333	57788.41	56000.58	43252.5	24030.18	11071.58	37062.67	3.044458	-0.76507
1221.922	622.6288	60423.4	58521.22	46658.46	21061.3	11745.65	41262.52	3.204259	-0.6486
735.3802	1041.755	61847.12	57587.43	48432.98	18060.01	12244.63	43342.77	3.255243	-0.60057
376.1912	1477.216	62852.19	54567.92	49104.11	15765.7	12604.08	43911.11	3.26705	-0.56657
155.1244	2087.28	64776.63	50560.52	49191.95	14303.45	12733.68	42665.37	3.236566	-0.53545
48.99802	2790.234	68041.28	46192.82	48694.64	13440.04	12654.5	39386.16	3.143147	-0.46992
11.98928	3572.18	73327.01	42562.55	47555.4	12533.02	12119.17	34825.29	2.944663	-0.42729
2.156813	4400.868	82492.57	40893.3	45843.79	11061.05	10825.39	29901.99	2.664341	-0.40271

2701.973	0	48508.09	43841.42	33096.45	26956.14	8491.139	27346.69	2.135616	-1.05572
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2767.583	92.3178	58485.16	51971.99	39927.69	31054.68	9495.258	32646.98	2.609302	-1.00115
2198.401	285.6392	62143.71	58755.19	44521.3	28009.3	10680.94	38088.17	3.012552	-0.89439
1740.612	557.2728	65452.2	62911.4	48064.05	25711.47	11247.29	42912.55	3.316284	-0.76188
1220.632	909.3175	66612.28	63504.45	49765.74	22486.86	11662.09	45825.12	3.508918	-0.64169
757.8078	1247.838	66471.2	62023.48	50126.98	19080.38	11947.39	47729.97	3.599732	-0.5868
395.8454	1686.4	66658.96	58879.94	49717.71	16090.52	12026.73	48143.85	3.647063	-0.56231
169.3263	2178.072	67626.46	54459.86	48700.56	13966.79	11970.65	46484.75	3.64861	-0.53032
57.74609	2751.873	70197.89	50024.51	47258.48	12536.15	11594.09	43079.21	3.582218	-0.47848
14.94661	3334.38	75073.65	46435.93	45651.98	11394.6	10926.78	38365.65	3.425418	-0.43667
2701.973	0	48508.09	43841.42	33096.45	26956.14	8491.139	27346.69	2.135616	-1.05572
2767.583	92.3178	58485.16	51971.99	39927.69	31054.68	9495.258	32646.98	2.607601	-1.00299
2437.231	281.8351	64497.9	59891.61	45227.71	30042.5	10458.99	38548.67	3.015267	-0.93426
2058.022	535.0667	68636.04	64974.13	48933.48	28660.76	10967.67	43672.35	3.361464	-0.84463
1568.714	853.0959	70221.43	66840.17	50693.81	25799.07	11327.55	47032.85	3.640454	-0.72238
1085.383	1141.118	70036.52	66645.47	51024.29	22383.61	11559.2	49612.93	3.82707	-0.62644
653.7831	1499.085	69409.39	64323.06	50433.41	18871.89	11614.4	50926.99	3.935974	-0.57313
520.9109	1733.124	71116.33	64543.15	49567.31	17710.45	11158.75	52914.26	4.01949	-0.50505
392.7899	1919.49	72571.94	64344.19	47682.28	15973.46	10208.16	54252.31	4.06636	-0.48972
249.0487	2094.911	73405.53	62771.02	45509.21	13661.63	9396.814	54289.19	4.110232	-0.48657
2701.973	0	48508.09	43841.42	33096.45	26956.14	8491.139	27346.69	2.135616	-1.05572
2767.583	92.3178	58485.16	51971.99	39927.69	31054.68	9495.258	32646.98	2.606071	-1.00486
2783.683	282.7678	68334.51	61297.8	46611.49	33555.92	10061.38	39212.41	3.063226	-0.97452
2605.444	535.3603	74443.54	67706.25	50727.74	34069.81	10427.04	44781.75	3.522897	-0.92912
2316.082	837.0964	78250.32	71721.44	52785.83	33223.58	10582.59	48822.87	3.928056	-0.87019
1980.414	1056.849	80225.1	74828.05	53265.35	31433.53	10501.48	52562.09	4.287897	-0.82257
1601.953	1280.032	80912.62	76490.95	52655.87	28852.27	10245.25	55601.05	4.625374	-0.76462
1229.145	1479.183	80502.67	76535.56	51036.7	25727.1	9820.371	57595.26	4.934061	-0.66715
880.6666	1669.476	79656.21	75166.01	48734.43	22159.17	9176.197	58753.82	5.152049	-0.59421
587.1139	1828.339	78828.88	72778.54	46295.81	18620.29	8539.322	59210.43	5.293856	-0.54642
2650.637	0	43727.62	41495.3	30742.02	16189.01	7938.579	24985.54	1.870916	-1.11517
2701.973	0	48508.09	43841.42	33096.45	18465	8491.139	27346.69	2.134948	-1.05654
2797.068	93.89901	59727.31	52716.84	40357.18	22125.34	9405.006	32981.81	2.633581	-1.02161
2808.293	285.5336	68866.35	61720.32	46819.63	23838.41	9981.251	39358.56	3.182663	-0.99157
2656.13	541.7463	75306.91	68424.8	51026.87	24208.44	10313.45	45012.7	3.756655	-0.95201
2405.745	850.5726	79598.42	72762.38	53112.1	23592.62	10339.7	49157.57	4.286486	-0.89687
2129.215	1076.905	82279.09	76402.04	53700.7	22515.07	10182.43	53070.78	4.776581	-0.85874
1823.589	1305.609	83939.99	78857.25	53206.55	21041.22	9828.849	56385.71	5.25394	-0.81058
1545.66	1517.689	84846.11	80214.13	51650	19518.6	9182.252	58834.64	5.706287	-0.72685
1287.616	1714.148	85501	80844.71	49552.22	17873.03	8450.834	60721.14	6.083381	-0.67222
1061.125	1853.532	86370.08	81342.41	47393.56	16360.62	7754.914	62344.05	6.425488	-0.62586
3061.114	96.36119		35972.25		23627.8	9063.896	24141.69	1.870916	-1.11517
2925.002	108.889		37388.92		25311.13	9291.674	25991.69	2.138911	-1.05226
2966.669	132.5557		55222.27		22161.13	6388.894	37888.92	2.679534	-0.92699
2215.002	455.2781		77694.51		13511.12	2902.78	49527.82	3.096875	-0.74187
2054.168	4300.003		68416.72		7713.895	808.334	47361.15	3.242353	-0.58318

4136.114	9500.008	51694.49	4383.337	0	42583.37	3.161707	-0.47103
7194.45	11261.12	34444.47	2001.113	0	38277.81	2.91258	-0.44464
9922.23	12841.68	31555.58	1021.112	0	40722.25	2.629362	-0.43927
11294.45	15172.23	31555.58	589.7227	0	46027.81	2.371128	-0.43818
11597.23	17366.68	30527.8	468.0559	0	49416.71	2.131112	-0.4291
11852.79	18930.57	30527.8	383.6114	0	54277.82	1.890534	-0.41594
3061.114	96.36119	35972.25	23627.8	9063.896	24141.69	1.870916	-1.11517
2925.002	108.889	37388.92	25311.13	9291.674	25991.69	2.138941	-1.05221
2966.669	132.5557	55222.27	22161.13	6388.894	37888.92	2.678085	-0.92715
2908.336	213.9724	80888.95	14163.9	2902.78	52416.71	3.142186	-0.76715
2958.336	960.2785	88027.85	8544.451	808.334	57305.6	3.435167	-0.62639
2886.113	2571.669	85055.62	5450.004	0	60555.6	3.558382	-0.50837
4419.448	4313.892	69361.17	3011.114	0	57055.6	3.523943	-0.46815
7475.006	6377.783	53305.6	1959.724	0	52194.49	3.382893	-0.43928
10416.68	9902.786	44888.92	1574.168	0	53388.93	3.176578	-0.4211
12936.12	13519.46	39388.92	1493.89	0	54083.38	2.919882	-0.42299
14225.01	16419.46	37527.81	1365.834	0	58555.6	2.656269	-0.42371
3061.114	96.36119	35972.25	23627.8	9063.896	24141.69	1.870916	-1.11517
2925.002	108.889	37388.92	25311.13	9291.674	25991.69	2.138945	-1.05221
2966.669	132.5557	55222.27	22161.13	6388.894	37888.92	2.678056	-0.92803
3369.447	202.8613	76916.73	15963.9	2902.78	52388.93	3.172607	-0.78732
3483.336	651.6672	86583.4	10952.79	808.334	58777.82	3.558691	-0.65113
3400.003	1696.946	90861.18	7444.45	0	65583.39	3.778043	-0.53605
3386.114	3086.114	84000.07	4497.226	0	66972.28	3.875289	-0.4993
5105.56	4702.782	67611.17	2728.058	0	61805.61	3.903814	-0.46194
7866.673	7102.783	55944.49	2101.668	0	60861.16	3.832811	-0.43135
11361.12	10527.79	49583.37	2275.28	0	60833.38	3.660717	-0.4146
14350.01	13119.45	45250.04	2318.891	0	63083.38	3.431628	-0.40389
3061.114	96.36119	35972.25	23627.8	9063.896	24141.69	1.870916	-1.11517
2925.002	108.889	37388.92	25311.13	9291.674	25991.69	2.138944	-1.05221
2966.669	132.5557	55222.27	22161.13	6388.894	37888.92	2.678023	-0.92861
3402.781	195.8613	76805.62	16761.12	2902.78	52527.82	3.179688	-0.79923
3952.781	536.6671	87055.63	12816.68	808.334	59611.16	3.616277	-0.67046
4394.448	1255.279	95000.08	9097.23	0	68638.94	3.910007	-0.56386
4141.67	1883.335	95333.41	6358.338	0	74472.28	4.082963	-0.53123
4225.003	2471.113	84555.62	4280.559	0	73000.06	4.214922	-0.49825
5086.115	3644.447	78166.73	3450.003	0	75361.17	4.301837	-0.47013
6680.561	6116.672	72666.72	3222.225	0	76305.62	4.3241	-0.44489
7908.34	8075.006	70527.83	2938.891	0	81777.84	4.312506	-0.42656
3061.114	96.36119	35972.25	23627.8	9063.896	24141.69	1.870916	-1.11517
2925.002	108.889	37388.92	25311.13	9291.674	25991.69	2.138942	-1.05221
2966.669	132.5557	55222.27	22161.13	6388.894	37888.92	2.676709	-0.93024
3475.003	219.528	77222.28	17947.24	2902.78	53277.82	3.191565	-0.83427
4280.559	400.8337	89361.18	15847.23	808.334	61944.49	3.720313	-0.73787
5238.893	889.7229	100805.6	12877.79	0	73083.39	4.204516	-0.63106
5861.116	1421.946	107333.4	9577.785	0	82861.18	4.607925	-0.59371
5941.671	1675.001	102833.4	7141.672	0	85722.29	4.949741	-0.55274

5602.782	1893.335	99111.19	5591.671	0	90138.96	5.207266	-0.51623
5411.115	2822.224	91166.74	4366.67	0	89194.52	5.378522	-0.48478
5661.116	4197.226	84972.29	3711.114	0	93055.63	5.504735	-0.45672
3061.114	96.36119	35972.25	23627.8	9063.896	24141.69	1.870916	-1.11517
2925.002	108.889	37388.92	25311.13	9291.674	25991.69	2.137968	-1.05339
2930.558	134.7779	55666.71	22627.8	6388.894	38027.81	2.708892	-0.95575
3483.336	258.9447	78416.73	18841.68	2902.78	54000.04	3.336422	-0.87824
4491.67	491.9448	90750.07	17713.9	808.334	64138.94	4.053595	-0.81424
5541.671	929.4452	103361.2	15369.46	0	76916.73	4.837492	-0.72856
5950.005	1322.501	114861.2	12163.9	0	90416.74	5.640415	-0.70926
5891.671	1598.335	121027.9	9408.341	0	99083.41	6.479087	-0.68045
5675.005	1901.668	130472.3	7216.672	0	111639	7.307217	-0.64595
5725.005	2174.446	129472.3	5450.004	0	114666.8	8.052744	-0.60579
6075.005	2550.835	121555.7	4125.003	0	117000.1	8.69777	-0.55226

Radiative forcing (methane)	Radiative forcing (CO2)	Radiative forcing (f-gases)	Radiative forcing (Kyoto gases)	Radiative forcing (nitrous oxide)	GDP	Cropland	Forest	Pasture	Urban area
0.562305	1.689784	0.021105	2.34675	0.155711	5.74E+13	1.55E+09	3.73E+09	3.19E+09	67192000
0.588276	1.837859	0.031102	2.539069	0.167804	6.85E+13	1.58E+09	3.71E+09	3.19E+09	62963563
0.587912	2.126495	0.05629	2.87373	0.188953	1.02E+14	1.53E+09	3.72E+09	3.1E+09	77418556
0.507789	2.286914	0.060184	2.983996	0.203256	1.56E+14	1.52E+09	3.77E+09	3E+09	91698694
0.422359	2.297562	0.047899	2.918372	0.212165	2.23E+14	1.61E+09	3.81E+09	2.91E+09	1.05E+08
0.360978	2.233642	0.040867	2.802596	0.21973	2.91E+14	1.63E+09	3.91E+09	2.79E+09	1.16E+08
0.322647	2.14897	0.037774	2.688533	0.226153	3.56E+14	1.65E+09	4E+09	2.68E+09	1.19E+08
0.302464	2.056453	0.036675	2.583887	0.232355	4.19E+14	1.68E+09	4.08E+09	2.59E+09	1.21E+08
0.285537	1.948056	0.036537	2.467311	0.238767	4.75E+14	1.75E+09	4.14E+09	2.53E+09	1.21E+08
0.26893	1.817973	0.036705	2.329769	0.24532	5.25E+14	1.77E+09	4.2E+09	2.47E+09	1.19E+08
0.253994	1.662189	0.036653	2.167739	0.251879	5.65E+14	1.79E+09	4.23E+09	2.4E+09	1.16E+08
0.562305	1.689784	0.021105	2.34675	0.155711	5.74E+13	1.55E+09	3.73E+09	3.19E+09	67192000
0.588276	1.837859	0.031102	2.539069	0.167804	6.85E+13	1.58E+09	3.71E+09	3.19E+09	62963563
0.593697	2.157672	0.062164	2.915987	0.189224	1.02E+14	1.53E+09	3.72E+09	3.1E+09	77418556
0.530861	2.434354	0.084949	3.177712	0.205083	1.56E+14	1.48E+09	3.77E+09	3E+09	91698694
0.456194	2.624037	0.077491	3.306604	0.215457	2.23E+14	1.51E+09	3.85E+09	2.91E+09	1.05E+08
0.398372	2.722558	0.058852	3.344597	0.222913	2.91E+14	1.52E+09	3.97E+09	2.79E+09	1.16E+08
0.359934	2.748165	0.048949	3.333662	0.229083	3.56E+14	1.55E+09	4.06E+09	2.68E+09	1.19E+08
0.333714	2.721972	0.044354	3.286307	0.234898	4.19E+14	1.6E+09	4.12E+09	2.59E+09	1.21E+08
0.305963	2.642602	0.042279	3.18728	0.241008	4.75E+14	1.72E+09	4.14E+09	2.53E+09	1.21E+08
0.283203	2.514044	0.0413	3.045488	0.248186	5.25E+14	1.82E+09	4.16E+09	2.47E+09	1.19E+08
0.267574	2.38049	0.040553	2.905152	0.255495	5.65E+14	1.77E+09	4.22E+09	2.4E+09	1.16E+08
0.562305	1.689784	0.021105	2.34675	0.155711	5.74E+13	1.55E+09	3.73E+09	3.19E+09	67192000
0.588276	1.837859	0.031102	2.539069	0.167804	6.85E+13	1.58E+09	3.71E+09	3.19E+09	62963563
0.614046	2.165302	0.064886	2.944814	0.190343	1.02E+14	1.54E+09	3.71E+09	3.12E+09	77418556
0.5851	2.480179	0.104262	3.293846	0.20981	1.56E+14	1.5E+09	3.75E+09	3.04E+09	91698694
0.518965	2.759221	0.130879	3.557826	0.224548	2.23E+14	1.53E+09	3.83E+09	2.95E+09	1.05E+08
0.46013	2.986978	0.138963	3.75372	0.234802	2.91E+14	1.54E+09	3.95E+09	2.83E+09	1.16E+08
0.417503	3.15954	0.130103	3.888342	0.242097	3.56E+14	1.54E+09	4.06E+09	2.71E+09	1.19E+08
0.377451	3.268606	0.117908	3.956422	0.247491	4.19E+14	1.56E+09	4.16E+09	2.63E+09	1.21E+08
0.337522	3.293187	0.098625	3.93196	0.251814	4.75E+14	1.6E+09	4.24E+09	2.56E+09	1.21E+08
0.303393	3.224016	0.076575	3.816512	0.256723	5.25E+14	1.74E+09	4.22E+09	2.5E+09	1.19E+08
0.281587	3.098069	0.064914	3.666768	0.263206	5.65E+14	1.84E+09	4.18E+09	2.43E+09	1.16E+08
0.562305	1.689784	0.021105	2.34675	0.155711	5.74E+13	1.55E+09	3.73E+09	3.19E+09	67192000
0.588276	1.837859	0.031102	2.539069	0.167804	6.85E+13	1.58E+09	3.71E+09	3.19E+09	62963563
0.616108	2.166663	0.065143	2.948266	0.190418	1.02E+14	1.54E+09	3.7E+09	3.13E+09	77418556
0.600012	2.491989	0.107422	3.322438	0.210713	1.56E+14	1.51E+09	3.74E+09	3.06E+09	91698694

0.558577	2.800595	0.150954	3.656641	0.228122	2.23E+14	1.54E+09	3.8E+09	2.98E+09	1.05E+08
0.517918	3.081786	0.193118	3.960117	0.242929	2.91E+14	1.55E+09	3.87E+09	2.86E+09	1.16E+08
0.482021	3.330038	0.227216	4.22383	0.254919	3.56E+14	1.55E+09	3.94E+09	2.74E+09	1.19E+08
0.441072	3.536311	0.241699	4.418094	0.263369	4.19E+14	1.56E+09	4.01E+09	2.66E+09	1.21E+08
0.395604	3.681662	0.225876	4.514041	0.268592	4.75E+14	1.61E+09	4.06E+09	2.59E+09	1.21E+08
0.351238	3.76573	0.206082	4.543719	0.271865	5.25E+14	1.63E+09	4.11E+09	2.52E+09	1.19E+08
0.31245	3.801884	0.189608	4.532638	0.274216	5.65E+14	1.62E+09	4.16E+09	2.46E+09	1.16E+08
0.562305	1.689784	0.021105	2.34675	0.155711	5.74E+13	1.55E+09	3.73E+09	3.19E+09	67192000
0.588276	1.837859	0.031102	2.539069	0.167804	6.85E+13	1.58E+09	3.71E+09	3.19E+09	62963563
0.620427	2.167961	0.06525	2.953577	0.190641	1.02E+14	1.55E+09	3.7E+09	3.14E+09	77418556
0.633706	2.504503	0.108899	3.366587	0.212134	1.56E+14	1.52E+09	3.7E+09	3.08E+09	91698694
0.640193	2.835057	0.159799	3.773374	0.231935	2.23E+14	1.55E+09	3.73E+09	3.01E+09	1.05E+08
0.631824	3.141208	0.212557	4.14256	0.249349	2.91E+14	1.57E+09	3.78E+09	2.89E+09	1.16E+08
0.61045	3.421694	0.257734	4.464824	0.26418	3.56E+14	1.57E+09	3.84E+09	2.78E+09	1.19E+08
0.581716	3.678986	0.297662	4.750294	0.276938	4.19E+14	1.58E+09	3.89E+09	2.69E+09	1.21E+08
0.542534	3.894973	0.334758	4.98104	0.288024	4.75E+14	1.61E+09	3.92E+09	2.62E+09	1.21E+08
0.49836	4.067145	0.365317	5.155511	0.297451	5.25E+14	1.63E+09	3.95E+09	2.55E+09	1.19E+08
0.459471	4.210662	0.383124	5.291111	0.30491	5.65E+14	1.6E+09	4E+09	2.49E+09	1.16E+08
0.562305	1.689784	0.021105	2.34675	0.155711	5.65E+13	1.54E+09	3.92E+09	3.43E+09	
0.588276	1.837859	0.031102	2.539069	0.167804	6.75E+13	1.55E+09	3.89E+09	3.42E+09	
0.61707	2.151473	0.06133	2.930644	0.190979	1.01E+14	1.61E+09	3.91E+09	3.38E+09	
0.58715	2.351585	0.077088	3.14249	0.212475	1.41E+14	1.68E+09	3.96E+09	3.36E+09	
0.509574	2.396929	0.075699	3.137563	0.22977	1.81E+14	1.73E+09	4.06E+09	3.16E+09	
0.435621	2.364166	0.076608	3.053658	0.240821	2.23E+14	1.76E+09	4.19E+09	2.95E+09	
0.380312	2.285698	0.079394	2.936336	0.246385	2.69E+14	1.8E+09	4.32E+09	2.75E+09	
0.338259	2.169025	0.082533	2.788741	0.248219	3.21E+14	1.87E+09	4.42E+09	2.58E+09	
0.301909	2.020294	0.084975	2.610428	0.247229	3.78E+14	1.91E+09	4.49E+09	2.44E+09	
0.271782	1.858256	0.086585	2.421552	0.244504	4.38E+14	1.93E+09	4.55E+09	2.33E+09	
0.249517	1.701561	0.087789	2.242835	0.240289	5.05E+14	1.94E+09	4.61E+09	2.24E+09	
0.562305	1.689784	0.021105	2.34675	0.155711	5.65E+13	1.54E+09	3.92E+09	3.43E+09	
0.588276	1.837859	0.031102	2.539069	0.167804	6.75E+13	1.55E+09	3.89E+09	3.42E+09	
0.617437	2.149903	0.061264	2.929337	0.190994	1.01E+14	1.62E+09	3.9E+09	3.38E+09	
0.60655	2.413017	0.078293	3.222621	0.213422	1.42E+14	1.68E+09	3.92E+09	3.39E+09	
0.559263	2.595962	0.080345	3.387617	0.233756	1.84E+14	1.73E+09	3.96E+09	3.36E+09	
0.496306	2.693107	0.084704	3.451632	0.249976	2.29E+14	1.78E+09	4.05E+09	3.28E+09	
0.449361	2.713744	0.089193	3.44877	0.262045	2.77E+14	1.82E+09	4.15E+09	3.12E+09	
0.420164	2.673226	0.092784	3.395633	0.270751	3.31E+14	1.89E+09	4.24E+09	2.98E+09	
0.395895	2.57974	0.096069	3.289546	0.275577	3.9E+14	1.96E+09	4.33E+09	2.85E+09	
0.366439	2.461945	0.098798	3.150762	0.277001	4.54E+14	2.01E+09	4.41E+09	2.73E+09	
0.33553	2.341671	0.101286	3.005621	0.27603	5.25E+14	2.04E+09	4.48E+09	2.61E+09	
0.562305	1.689784	0.021105	2.34675	0.155711	5.65E+13	1.54E+09	3.92E+09	3.43E+09	
0.588276	1.837859	0.031102	2.539069	0.167804	6.75E+13	1.55E+09	3.89E+09	3.42E+09	
0.618688	2.156237	0.06126	2.936828	0.191089	1.01E+14	1.62E+09	3.88E+09	3.4E+09	
0.621345	2.467845	0.083669	3.296106	0.214084	1.43E+14	1.66E+09	3.88E+09	3.43E+09	
0.592793	2.749819	0.090979	3.582878	0.235924	1.85E+14	1.72E+09	3.88E+09	3.43E+09	
0.537515	2.97831	0.094226	3.786408	0.254871	2.3E+14	1.77E+09	3.93E+09	3.39E+09	
0.488544	3.133864	0.09806	3.919573	0.270427	2.79E+14	1.82E+09	4.01E+09	3.33E+09	